Climate Change 2014: Impacts, Adaptation, and Vulnerability

SUMMARY FOR POLICYMAKERS

Drafting Authors
Christopher Field (USA), Vicente Barros (Argentina), Michael Mastrandrea (USA), Katharine Mach (USA), Mohamed Abdrabo (Egypt), Neil Adger (UK), Yury Anokhin (Russian Federation), Oleg Anisimov (Russian Federation), Douglas Arent (USA), Jonathon Barnett (Australia), Virginia Burkett (USA), Rongshuo Cai (China), Monalisa Chatterjee (USA/India), Stewart Cohen (Canada), Wolfgang Cramer (Germany), Purnamita Dasgupta (India), Debra Davidson (Canada), Fatima Denton (Gambia), Petra Döll (Germany), Kirstin Dow (USA), Yasuaki Hijioka (Japan), Ove Hoegh-Guldberg (Australia), Richard Jones (UK), Roger Jones (Australia), Roger Kitching (Australia), Sari Kovats (UK), Patricia Romero Lankao (Mexico), Joan Nymand Larsen (Iceland), Erda Lin (China), David Lobell (USA), Iñigo Losada (Spain), Graciela Magrin (Argentina), Jose Marengo (Brazil), Anil Markandya (Spain), Bruce McCarl (USA), Roger McLean (Australia), Linda Mearns (USA), Guy Midgley (South Africa), Nobuo Mimura (Japan), John Morton (UK), Isabelle Niang (Senegal), Ian Noble (Australia), Leonard Nurse (Barbados), Karen O'Brien (Norway), Taikan Oki (Japan), Lennart Olsson (Sweden), Michael Oppenheimer (USA), Jonathan Overpeck (USA), Joy Pereira (Malaysia), Elvira Poloczanska (Australia), John Porter (Denmark), Hans-O. Pörtner (Germany), Michael Prather (USA), Roger Pulwarty (USA), Andy Reisinger (New Zealand), Aromar Revi (India), Oliver Ruppel (Namibia), David Satterthwaite (UK), Daniela Schmidt (UK), Josef Settele (Germany), Kirk Smith (USA), Avelino Suarez (Cuba), Petra Tschakert (USA), Richard Tol (UK), Riccardo Valentini (Italy), Alicia Villamizar (Venezuela), Rachel Warren (UK), Thomas Wilbanks (USA), Poh Poh Wong (Singapore), Alistair Woodward (New Zealand), Gary Yohe (USA)

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INTRODUCTION

The Working Group II (WGII) contribution to the IPCC's Fifth Assessment Report (AR5) assesses the shifting patterns of risks and opportunities associated with climate change and provides information on how risks can be reduced through mitigation and adaptation.

Box SPM.1 defines central concepts, and Box SPM.2 introduces terms used to convey the degree of certainty in findings. Chapter sections in square brackets indicate the assessment supporting findings in this summary.

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Box SPM.1. Terms Critical for Understanding the Summary

Climate change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulation of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. In contrast, the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities that alter the atmospheric composition, and climate variability attributable to natural causes.

Exposure: The presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected.

Impacts: Effects on natural and human systems. In this report, the term "impacts" is used to refer to the effects on natural and human systems of physical events, of disasters, and of climate change.

Risk: The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk is often represented as probability of occurrence of a hazardous event(s) multiplied by the consequences if the event(s) occurs. This report assesses climate-related risks.

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, which seeks to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate.

Transformation: A change in the fundamental attributes of a system, often based on altered paradigms, goals, or values. Transformations can occur in technological or biological systems, financial structures, and regulatory, legislative, or administrative regimes.

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Box SPM.2. Communication of the Degree of Certainty in Assessment Findings

The WGII AR5 relies on two metrics for communicating the degree of certainty in assessment findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically, based on statistical analysis of observations or model results, or expert judgment.

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The summary terms to describe available evidence are: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. When author teams evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, a finding can include likelihood terms: v*irtually certain*, 99–100% probability; *very likely*, 90–100%; *likely*, 66–100%; *about as likely as not*, 33–66%; *unlikely*, 0–33%; *very unlikely*, 0–10%; and *exceptionally unlikely*, 0–1%. Additional terms used: *extremely likely*, 95– 100% probability; *more likely than not*, >50–100%; and *extremely unlikely*, 0–5%.

_____ END BOX SPM.2 HERE _____

A) IMPACTS, VULNERABILITIES, AND ADAPTATION IN A COMPLEX AND CHANGING WORLD

A.i. Observed Impacts and Vulnerabilities

Impacts of recent observed climate change on physical, biological, and human systems have been detected on all continents and in most oceans (*high confidence*). This conclusion is strengthened by observations since the IPCC Fourth Assessment Report (AR4) and through more extensive analyses of earlier observations. Most reported impacts of climate change are attributed to regional atmospheric and oceanic warming, with lower confidence in attribution to shifts in rainfall patterns. For many natural systems on land and in the ocean, new or stronger evidence exists for substantial and wide-ranging climate change impacts. For managed ecosystems and human systems, effects of changing social and economic factors often dominate over direct impacts of climate change. See Table SPM.1 for regional examples. [18.3-18.6]

[INSERT TABLE SPM.1 HERE
Table SPM.1: Observed impacts attributed to climate change with *medium* (*) or *high* (**) confidence, for physical, biological, and human systems across eight major world regions. [Tables 18-6, 18-7, 18-8, 18-9]]

Climatic and biophysical drivers interact with non-climatic drivers of vulnerability and exposure to shape differential risks and impacts (*very high confidence*). See Box SPM.3. Vulnerability and exposure of communities or social-ecological systems to climatic hazards are dynamic and thus varying across temporal and spatial scales. [13.1, 14.1, 14.2, 15.2.4, 19.6.1]

Impacts from recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (*very high confidence*). These experiences are consistent with a significant adaptation deficit in developing and developed countries for some sectors and within some regions. [10.3.1, 10.7.3, 13.2.1, 18.4.4, 18.4.7, 25.8.1, 26.6, 26.7, Tables 18-4, 23-3, 25-1, Boxes 25-5, 25-6, 25-8]

Hydrological systems have changed in many regions due to changing rainfall or melting glaciers, affecting water resources, water quality, and sediment transport (*medium confidence*). The duration of droughts in some regions has been altered by climate change. In many river systems, the frequency of floods has been altered by climate change (*low* to *medium confidence*). Widespread changes and degradation of permafrost in high-latitude and high-elevation mountain regions have been observed over the past years and decades (*high confidence*). [3.2.3, 18.3.1, 18.5]

Terrestrial plant and animal species have shifted their ranges and seasonal activities and altered their abundance, in response to climate change in the past, and they are doing so now in many regions (*high confidence*). Increases in the frequency or intensity of ecosystem disturbances due to fires, pest outbreaks, wind-storms, and droughts have been detected in many parts of the world (*medium confidence*). There is *very low confidence* that most observed species extinctions can be attributed to recent climate warming. However, recent warming has played a role in extinctions of Central American amphibians (*medium confidence*). [4.2-4.4, 18.3.2, 18.5]

Several major terrestrial ecosystems are undergoing broad-scale changes that can be characterized as early warnings for coming regime shifts, in part due to climate change. Climate change is a driver of widespread shrub encroachment in the Arctic tundra (*high confidence*) and of boreal forest tree mortality (*low confidence*). In Central and South America, conversion of natural ecosystems is currently the main cause of biodiversity and

ecosystem loss and a driver of anthropogenic climate change. However, observed recession and degradation of the Amazon forest cannot be attributed to climate change. [18.3.2, 18.5.6, 18.5.7, 27.2.2, 27.3.2]

Warming is causing shifts in marine species' geographical distribution, abundance, migration patterns, and timing of seasonal activities, resulting in altered species interactions (*high confidence*). There are many observations of poleward shifts in the distribution and abundance of fishes and invertebrates and/or of their shifts to deeper and cooler waters. Warming-induced stratification, reduced intensity of ocean circulation, and the breakdown of organic matter by organisms are expanding hypoxic regions that constrain the habitat of oxygen-dependent marine animals, plants, and microbes. In Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts in the oceans. [6.1-3, 6.5, 18.3, 30.4-5, Box CC-CR]

Effects of climate change on food production are evident in several regions (*high agreement, medium evidence*). Yields have increased in mid-to-high-latitude regions due to warming and higher CO_2 (*low confidence*) and decreased in other, mainly low-latitude regions due to water shortages and higher temperatures (*medium confidence*). Overall, negative impacts have been more common than positive ones (*high confidence*). Since AR4, there have been several periods of rapid food price increases, demonstrating partial sensitivity of current markets to climate variability. Interactions among production factors (e.g., CO_2 and ozone, mean temperature, extremes, water, nitrogen) can alter primary food production in complex ways (*high agreement, medium evidence*). [7.2, 7.3, 7.4, 18.4.1, Figures 7-2 to 7-7, Tables 7-1, 18-9]

Prevailing rural development constraints, such as low levels of educational attainment, environmental degradation, gender inequality, and remoteness from decisionmakers, create additional vulnerabilities to climate change (*high confidence*). In developing countries, rural people are subject to multiple non-climate stressors, such as under-investment in agriculture and land-policy problems (*high* to *very high confidence*). [9.2, 9.3.1, 9.3.5, 9.4.4, Table 9-1]

In recent decades, climate change has *likely* contributed to levels of ill-health though the present world-wide burden of ill-health from climate change is relatively small compared with other stressors on health and is not well quantified. Changes in temperature, rainfall, and sea-level have altered distribution of some disease vectors, increased heat wave casualties, and reduced food production for vulnerable populations (*medium confidence*). Climate change is a multiplier of existing vulnerabilities affecting health outcomes (*high confidence*). [11.3, 11.4, 18.4.5, 22.3.5, Box 11-4]

People living in places affected by violent conflict are particularly vulnerable to climate change (*high agreement, limited evidence*). A causal effect of climate change and variability on violence is contested, although there is *robust evidence* that shows that low per capita incomes, economic contraction, and inconsistent state institutions, factors sensitive to climate change, are associated with the incidence of civil wars. [12.5, 19.6.1]

Climate change constitutes an additional burden for the rural and urban poor (*very high confidence*). Urban and rural transient poor who face multiple deprivations can slide into chronic poverty as a result of extreme weather events, or a series of events, when they are unable to rebuild their eroded assets (*high agreement, limited evidence*). Preexisting gender inequalities are increased or highlighted by weather events and climate. Often, the more affluent can better take advantage of shocks and crises, given their flexible assets and power status. [13.1, 13.2.1, 13.3]

_____ START BOX SPM.3 HERE _____

Box SPM.3. Multidimensional Vulnerability to Climate Change

People who are socially, economically, culturally, politically, or institutionally marginalized are typically most at risk from adverse impacts of climate change and climate change responses. Such heightened vulnerability is related not only to income and assets but also to gender, class, race, ethnicity, age, and (dis)ability (Box SPM.3 Figure 1). Other dimensions include resource access, location, legal systems, and voice. Understanding differential adaptive capacity for individuals, households, and communities requires attention to multidimensional inequality, deprivation, and power. It also benefits from attention to context-specific interactions in social-ecological systems that contribute to differential vulnerability. [8.1.4, 9.3.5, 9.4.1, 11.4.1, 11.5, 13.2.1, 19.6.1]

[INSERT BOX SPM.3 FIGURE 1 HERE
Box SPM.3 Figure 1: Intersecting, simultaneous, and dynamic axes of privilege and marginalization, shaped by people's multiple identities and embedded in uneven power relations and development pathways. Together, they result in differential vulnerability to the same exposure to climate change and climate responses. [Figure 13-4]]

_____ END BOX SPM.3 HERE _____

A.ii. Adaptation Experience

Human and natural systems respond to climate and its effects. Natural systems have some potential to adapt, and are adapting, through ecological and evolutionary processes, and humans may intervene to promote particular adjustments. Responses in human systems include coping with climate variability and extremes, and managing risks through planned adaptation to climate change impacts. Adaptation can be motivated by broader vulnerability-reduction and development objectives, such as reducing existing adaptation deficits to current climate. [14.1]

Adaptation activity is increasing and becoming more integrated within wider policy frameworks (*high confidence*). Adaptation planning is transitioning from a phase of awareness and promotion to the construction of responses in societies (*high agreement, robust evidence*). [14.3.4, 14.4.2, 15.2, 15.3.1]

Awareness of climate risks and vulnerabilities, and the need for adaptation, does not always lead to action (*high confidence*). Numerous assessments have led to higher awareness among decisionmakers and stakeholders of climate risks and adaptation needs and options. However, in most cases this awareness of changing risks has not been translated into adjustments of ongoing activities or risk management planning. In order to facilitate such integration into decision-making, assessments may need to be linked more directly to particular decisions, with information tailored to support the decisionmaking process. [2.3, 14.5, 14.6]

The diversity of adaptation experience, including corresponding constraints and opportunities, can be seen in specific geographic contexts (see also Table SPM.2):

- **The scale and concentration of urban climate risk and hence the need for adaptation are being acknowledged, but responses are weak except for a handful of cities largely in high-income countries (*medium confidence*).** Examples of approaches to adaptation have included the designation of a unit within city government with responsibility for adaptation, measures to involve key sectors so they understand why they need to engage with adaptation, local champions to initiate measures and ensure continuity, and the importance of dialogue and discussion with all key stakeholders. City-based disaster risk reduction is a strong foundation around which to build urban climate resilience (*high confidence*). [8.2, 8.3, 8.4, 8.5]
- **Gender, the supply of information for decision-making, and the role of social capital in building resilience are all key issues for adaptation in rural areas (*high confidence*).** Constraints to adaptation come from lack of access to credit, land, water, technology, markets, and information, and constraints are particularly pronounced in developing countries. [9.4.1, 9.4.3, 9.4.4]
- **In many African countries, national governments are initiating governance systems for adaptation (*high agreement, medium evidence*).** Efforts such as disaster risk reduction, social protection, climate-resilient infrastructure, ecosystem restoration, and livelihood diversification are reducing vulnerability and enhancing resilience, but this is still largely confined to local scales and isolated initiatives. [22.4.4, 22.4.5, 22.6.2]
- **In Europe, adaptation policy has been developed at international (EU), national, and local government levels, but so far evidence relates to studies of the prioritization of options, and there is limited systematic information on current implementation or effectiveness.** Some adaptation planning has been integrated into coastal and water management, as well as disaster risk management. There is little evidence of adaptation planning in rural development, land-use planning, or conservation. [23.6.4, 23.7, Box 23-2]
- **In Australasia, adaptation is already occurring and adaptation planning is becoming embedded in planning processes, mostly at the conceptual rather than implementation level (*high agreement, robust evidence*).** Planning for sea-level rise and, in Australia, for reduced water availability is becoming widely adopted. Adaptive capacity is generally high in many Australasian human systems, but implementation faces major constraints especially for transformative responses at local and community levels (*high confidence*). Constraints on implementation arise from: uncertainty of projected impacts; limited financial and human resources; limited integration of different levels of governance; and different values and beliefs relating to the existence of climate change and to objects and places at risk. [25.4, 25.10.3, Boxes 25-1, 25-2, and 25-9]

- **In North America, while different tiers of government are assessing their climate vulnerabilities and designing adaptation actions and programs, there has been more leadership in adaptation planning at the local level (*high confidence*).** Important barriers exist to effective adaptation such as path dependency, asymmetries in access to information, top-down decision making, and lack of assets, options, funding, staff, horizontal and vertical coordination, and social capital. The few examples of proactive adaptation anticipating future climate impacts are largely found in sectors with longer-term decision-making, including energy and public infrastructure. [26.7, 26.8, 26.9]
- **In the Arctic, indigenous people have a high adaptive capacity and have begun to develop novel solutions to adapt to climate changes combining traditional and scientific knowledge and co-producing climate studies with scientific partners.** [28.2.4, 28.2.7, 28.4.1]

[INSERT TABLE SPM.2 HERE
Table SPM.2: Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.]

B) DECISIONMAKING IN A COMPLEX WORLD: UNDERSTANDING APPROACHES TO MANAGING RISKS THROUGH ADAPTATION

Managing the risks of climate change involves decisions with implications for future society, economies, environment, and climate. Robust decisions can be effective across a range of possible futures (see Box SPM.4). Fundamentally, adaptation to climate change can be considered an iterative process with continuing learning about risks and the effectiveness of risk management actions.

B.i. Determinants and Iterative Management of Risk

Risk in the context of climate change is produced through the interaction of changing physical characteristics of the climate system with evolving characteristics of human, socioeconomic, and biological systems (exposure and vulnerability). See Figure SPM.1. Alternative development paths influence risk both by changing the likelihood of physical impacts (through their effects on greenhouse gas emissions) and by altering vulnerability and exposure. [2.1.1, 19.1, 19.2, Fig.19-1]

Due to the uncertainty, dynamic complexity, and short-to-long timeframes associated with climate change, robust adaptation efforts require iterative risk management strategies (*high agreement, medium evidence*). While no-regret, low-regret, and win-win strategies have attracted attention in the past, there is increasing recognition that adaptive responses will entail acting in the face of continuing uncertainty about the extent of climate change, the nature of its impacts, and adaptation needs. Iterative risk management involves an ongoing process of assessment, action, reassessment, and response that may need to be applied under climate change for decades, if not longer. Monitoring and evaluation are important learning tools in this process. See Figure SPM.2. [2.1.2, 2.2.1, 2.3.1, 14.1, 14.3.4, 15.2.3, 15.3.3, 20.5]

[INSERT FIGURE SPM.1 HERE
Figure SPM.1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. Vulnerability and exposure are, as the figure shows, largely the result of socioeconomic development pathways and societal conditions. Changes in both the climate system (left) and development processes (right) are key drivers of the different core components (vulnerability, exposure, and physical hazards) that constitute risk. The definition and use of “key” and “emergent” are indicated in Section C.ii. [19.1, Figure 19-1]]

[INSERT FIGURE SPM.2 HERE
Figure SPM.2: Illustration of iterative response to climate change. (A) Four main phases of planned adaptation as a cyclic, iterative process: needs, planning, implementation, and evaluation. Efforts in adaptation can be linked with development or disaster risk management. Adaptation governance at multiple scales underlies capacity. (B) In the

context of iterative risk management, each individual adaptation decision cycle comprises well known aspects of risk assessment and management. (C) A sequence of adaptation decisions creates an adaptation pathway. Some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but there is no single correct adaptation pathway and judgment of outcomes depends strongly on societal values, expectations, and goals. [Figures 15-1, 16-2, 25-6]]

B.ii. Principles for Effective Adaptation

Experience in the practice of adaptation serves to clarify the opportunities for, and the most significant barriers to, adaptation and the synergies and tradeoffs with other societal goals. Types of responses to climate change are overviewed in Table SPM.3.

[INSERT TABLE SPM.3 HERE
Table SPM.3: Entry points, strategies, measures, and options for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples given can be relevant to more than one category.]

Actors at all geographical and institutional levels and in different development contexts have opportunities to facilitate, initiate, and implement effective adaptation action (*medium agreement, medium evidence*). Because adaptation is a multidimensional issue involving many state and non-state actors functioning at local to global scales, coordination of roles and responsibilities enhances institutional networking for effective implementation (*high agreement, medium evidence*) (Figure SPM.2A). National governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy frameworks, creation of legal frameworks, actions to protect vulnerable groups, and financial support to other levels of government (*high agreement, robust evidence*). Among the many actors and roles associated with adaptation, those associated with local governance and with the private sector are increasingly recognized as critical to progress (*high confidence*), as these groups bear responsibility for translating the top-down flow of risk information and financing, and for scaling up efforts of communities and households in identifying and implementing selected adaptation actions. [2.3.4, 14.4, 15.2.2, 15.2.3, 15.4, 16.6]

Strategies and actions can be pursued now that increase climate resilience while at the same time helping to improve human livelihoods, social and economic well-being, and responsible environmental management (*high confidence*). Adaptation actions can provide significant co-benefits such as alleviating poverty and enhancing development especially in developing countries. Improving resilience through an emphasis on disaster risk reduction has become increasingly common (*high agreement, medium evidence*). Efforts to improve ecosystem resilience can benefit adaptation. Building climate resilience in cities can involve ecosystem-based adaptation with water and food systems as foci (*medium confidence*). [2.3.4, 2.4.2, 8.3, 8.5, 14.3.4, 14.4.2, 15.2, 15.3.1, 17.2.7, 17.4.4, 20.6.2, 29.6]

Mainstreaming facilitates integration of adaptation into planning and decisionmaking and embeds climate-sensitive thinking in existing and new institutions and organizations (*high confidence*). Mainstreaming promotes synergies with development planning, enables the blending of multiple funding streams, and reduces the possibility of maladaptive actions. [14.3.4, 14.4.2, 16.6, 17.2.7, 17.4.4]

Constraints to adaptation planning and implementation include availability of resources and uncertainties about future climate and disaster risk at national and regional scales (*high agreement, robust evidence*). The manner in which constraints manifest and their implications for capacity to achieve adaptation objectives vary significantly across regions and sectors and across social and temporal scales. [16.2, 16.3, 17.2.6, 17.3, 17.5.4]

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*high confidence*). Instruments comprise risk sharing and transfer mechanisms, loans including public-private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including land taxes, direct investment, norms and regulations, behavioral approaches, and institutional innovations. Applicable risk financing mechanisms across scales comprise informal and traditional risk sharing, such as relying on kinship networks, as well as market-based instruments including microinsurance, insurance, reinsurance, and national, regional, and global risk pools (*medium confidence*). [8.4, 10.7, 10.9, 17.3.4, 17.3.6, 17.4, 17.5]

Intervention in one location or sector can increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change (*medium confidence*). Such maladaptation can result from decisions where greater emphasis is placed on short-term outcomes ahead of longer-term threats, or from decisions that discount, or fail to consider, the full range of interactions arising from planned actions. See also Figure SPM.2C. [14.7.1, 14.7.2]

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Box SPM.4. Characterizing the Future

While there are many possible scenarios for future climate change and societal development, current decisions narrow future options. New risks will emerge in the coming decades as a result of past emissions and current socioeconomic trends. Societal responses, particularly adaptations, will influence outcomes during this era of climate responsibility. In contrast, benefits of current mitigation efforts will emerge over a longer period. Future risks during this longer-term era of climate options are thus linked to current mitigation and development choices.

Trends in vulnerability, exposure, and climate, as well as weather and seasonal forecasting of climate variability, can inform decisions in the era of climate responsibility. Climate and impact model projections become increasingly relevant for climate-affected decisions playing out over the longer term, recognizing that uncertainties about future vulnerability and exposure also increase over time. [21.3.3, 21.5.1, 21.5.3]

Scenarios are a vital part of managing uncertainty. [2.2.1] Scenarios provide a mechanism for characterizing possible socioeconomic futures and climate change outcomes. Socioeconomic factors influence not only greenhouse gas emissions but also the size and location of populations at risk from various climate change impacts, the differential vulnerability of these populations, and their capacities to adapt.

Modeled future impacts assessed in this report draw on a combination of climate model simulations using SRES scenarios (CMIP3) and new climate model simulations using the Representative Concentration Pathway (RCP) scenarios (CMIP5). The four RCPs reflect different levels of mitigation, leading to 21st century radiative forcing levels of 2.6, 4.5, 6.0, and 8.5 W m^{-2} (see WGI AR5 Chapters 1, 6, 11, and 12). Box SPM.4 Figure 1 illustrates alternative climate futures, under RCPs 4.5 and 8.5, along with observed temperature and precipitation changes. [1.1.3, Box CC-RC]

[INSERT BOX SPM.4 FIGURE 1 HERE
Box SUM.4 Figure 1: Changes in annual average temperature (A) and precipitation (B). For observations (top map, A and B; CRU), differences are shown over land between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For projections (bottom four maps, A and B; CMIP5), four classes of results are displayed. (1) White indicates areas where for >66% of models the annual average change is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions, more than 2/3 of models show no significant change in the annual average using this measure of significance, although this does not imply no significant change at seasonal or shorter time-scales such as months to days. (2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions, more than 2/3 of models show a significant change in annual average, but less than 2/3 agree on whether it will increase or decrease. (3) Colors with white circles indicate the change averaged over all models where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on whether the annual average will increase or decrease. In these regions, more than 2/3 of models show a significant change in annual average and more than 2/3 (but less than 90%) agree on whether it will increase or decrease. (4) Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether the annual average will increase or decrease. For models that have provided multiple realizations for the climate of the recent past and the future, results from each realization were first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-

noise ratios were calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065. See also Annex I of WGI AR5. [Box CC-RC]]

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C) FUTURE RISKS AND CHOICES: RISKS AND POTENTIAL FOR ADAPTATION

Assessment of the full range of potential future impacts, not only the most likely outcomes, provides a basis for understanding future risks. This section covers future risks across sectors and regions, and their sensitivity to the magnitude and rate of climate change, to characteristics of development that affect vulnerability, and to policy choices. It elucidates how and when choices matter in reducing future risks and highlights the differing timeframes for mitigation and adaptation benefits within the eras of climate responsibility and climate options.

C.i. Sectoral and Regional Risks

Freshwater resources

Projected climate changes would change hydrological regimes substantially (*high agreement, robust evidence*). Runoff and groundwater recharge are projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions, controlled mainly by changes in precipitation. Projected climate changes imply large changes in the frequency of floods. Climate change is projected to reduce renewable water resources in most semi-arid and arid regions, potentially affecting food security. Impacts of climate change on water resources are expected to reduce economic growth, particularly in developing countries (*high agreement, limited evidence*). [3.2.5, 3.4, 3.5, 3.6.5, Table 3-2, WGI AR5 12.4.5]

Adaptive water management techniques, such as scenario planning, learning-based approaches, and flexible solutions, offer an opportunity to address uncertainty due to climate change (*high agreement, limited evidence*). Barriers include lack of technical capacity, financial resources, awareness, and communication. A low-emissions pathway reduces damage costs and costs of adaptation. [3.4, 3.5, 3.6, 3.7.2]

Terrestrial and inland water systems

Direct human impacts such as land-use change, pollution, and water resource development will continue to dominate threats to freshwater ecosystems (*high confidence*) and terrestrial ecosystems (*medium confidence*) with climate change becoming an increasing additional stress through the century, especially for high-warming scenarios (e.g., RCP 6.0 and 8.5). Even for mid-range rates of climate change (i.e., RCP 4.5 and 6.0 scenarios) many species will be unable to move fast enough to track suitable climates (*medium confidence*). See Figure SPM.3. Projected climate changes imply increased extinction risk for a substantial fraction of species during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, over-exploitation, and invasive species (*very high confidence*). Forests may be more sensitive to future climate change than reported in AR4, and tree mortality and forest dieback could become a problem in many regions much sooner than previously anticipated (*medium confidence*). [4.2.4, 4.3, 4.4.1, Box CC-RF]

Carbon stored in land and freshwater ecosystems in the form of plant biomass and soil organic matter has increased over the past two decades (*virtually certain*). The terrestrial carbon sink is offset to a large degree by carbon released to the atmosphere through forest conversion to farm and grazing land and through forest degradation (*high confidence*). The carbon stored thus far in terrestrial ecosystems is vulnerable to loss back to the atmosphere as a result of climate change and land-use change (*medium confidence*). [4.2, 4.3, Box 4-4]

Management actions can reduce, but not eliminate, exposure to climate-driven ecosystem impacts and can increase ecosystem adaptability (*high confidence*). Adaptive capacity of ecosystems can be increased by reducing other stresses, maintaining a large pool of genetic diversity and functional evolutionary processes, assisting translocation, and manipulating disturbance regimes. [4.4.1, 4.4.3]

Terrestrial and freshwater ecosystems can, when pushed by climate change, cross "tipping points" and abruptly change in composition, structure, and function (*high confidence*). The crossing of these tipping

points will result in significant increases in carbon emissions to the atmosphere (*medium confidence*). Examples include abrupt transformation of the ecology and albedo of the boreal-arctic system (*low confidence*) and of the Amazon forest to more open, dry-adapted ecosystems (*low confidence*). [4.2, 4.3.3, Box 4-3, 4-4, Figure 4-10]

[INSERT FIGURE SPM.3 HERE
Figure SPM.3: Synthetic overview of projected abilities of some terrestrial and freshwater species to track climate by movement across landscapes. (A) Rates of climate change for global land areas. Black dotted line shows observed rates of climate change. Other rates were calculated from the CMIP5 ensemble for the historical period (black heavy line, with upper and lower bounds as light black lines) and for the future based on the four RCPs. A lower bound is given for RCP 2.6, and an upper bound for RCP 8.5. (B) Corresponding climate velocities, providing indication of the speed at which species' ranges would need to move to track changing climatic conditions. In mountainous areas with low climate velocities, species would only need to move short distances upslope to track a warming climate. In flat areas with high climate velocities, such as the Amazon basin, species would need to move large distances to track a warming climate. (C) Maximum estimated rates of displacement of several terrestrial and freshwater species groups, indicating how fast these groups can move across landscapes. Rates of species displacement are well defined for plants, especially trees, but less well defined for other groups. Displacement rates do not generally account for biotic interactions or human intervention that may speed or hinder dispersal. The thin red arrows give an example of interpretation: a rate of climate change of 0.065 °C/yr (approximately equal to projected rates by mid-century for RCP 8.5) corresponds to ~2.2 km/yr global average climate velocity. This global-average velocity would exceed projected maximum capacity for displacement for most plants, most primates, many rodents, and some less mobile species of other groups. For RCP 2.6, most species would be able to track climate by mid-century. Color gradient in panel A provides overall representation of the ability of species to track climate change. Detailed spatial analyses and maps of species displacement can be found in the references cited in WGII Chapter 4. E.t ungulates = even-toed ungulates; Phyto. insects = phytophagous (herbivorous) insects; Fw. mollusks = freshwater mollusks. [Figure 4-6]]

Coastal systems and low-lying areas

Due to relative sea-level rise, coastal systems and low-lying areas will increasingly experience adverse impacts associated with submergence and flooding from extreme coastal high water levels (*high confidence*). The population and assets exposed to coastal risk as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, urbanization, and coastward migration. Under medium population projections, population exposed to the 100-year coastal flood is expected to increase from 271 million in 2010 to 345 million in 2050 due to socioeconomic development only. By 2100, without adaptation, the majority of people projected to be affected by coastal flooding and displaced due to inundation and erosion will be in East, Southeast, and South Asia. In 2100, for medium socioeconomic development assumptions and a 1.26 m sea-level rise, the expected direct global annual cost of coastal flooding may reach 300 US$ billion per year without adaptation and 90 US$ billion per year with adaptation, including costs of adaptation and residual damages. [5.3, 5.4.3, 5.5.3]

Acidification and warming of coastal waters will continue with significant consequences for coastal ecosystems (***high confidence***). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*). [5.4.2, 6.2, 6.3, 6.5.2, 30.4, 30.5, Box CC-CR, CC-OA]

Marine systems

Through species gains and losses in response to warming, the diversity of marine animals and plants will increase at mid and high latitudes (*high confidence*) and fall at tropical latitudes (*low confidence*), leading to large-scale redistribution of global catch potential for fishes and invertebrates (*medium confidence*). Animal displacements are projected to lead to a 30–70% increase in the fisheries yield in high-latitude regions but a drop of 40–60% in the tropics by 2055 relative to 2005 under the SRES A1B scenario (*medium confidence* for general trend of shifting fisheries yields, *low confidence* for magnitude of change). See Figure SPM.4. [6.2.5, 6.3, 6.4, 6.5]

Impacts on ocean ecosystems and processes reveal significant regional differences that will benefit from differing policies and adaptation approaches (*medium agreement, medium evidence*). Building dynamic

fisheries management and sustainable aquaculture provides opportunities for adaptation to changes in the distribution and productivity of fish stocks (*high agreement, medium evidence*). [6.5, 7.5.1, 30.5.5, 30.6.3]

Changes to surface winds, sea level, wave height, and storm intensity will increase the risks associated with coastal and ocean based industries such as shipping, oil, gas, and mineral extraction (*medium agreement, medium evidence*). New opportunities as well as international issues over access and vulnerability are expected as waters warm, particularly in high latitude regions. [30.6, 6.5]

[INSERT FIGURE SPM.4 HERE
Figure SPM.4: (A) Multi-model mean changes of projected net primary production. To indicate consistency in the sign of change, regions are stippled where all models (four in total) agree on the sign of change. Changes are annual means under SRES A2 for the period 2080 to 2099 relative to 1870 to 1889. (B) A projection of maximum fisheries catch potential of 1000 species of exploited fishes and invertebrates from 2000 to 2050 under SRES A1B. (C) Example of changes occurring within fisheries across the ocean. [Figures 6-14, 6-15, and 30-15]]

Food production systems and food security

Without adaptation, warming of up to 2°C local temperatures is expected to reduce yields on average for the major cereals (wheat, rice, and maize) in temperate regions, although many individual locations may benefit (*medium confidence*). There is confirmation that warming up to 2°C will decrease yields in low-latitude tropical regions (*medium agreement, robust evidence*). Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. From the 2070s onwards, all of the positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are *very likely* by this time and substantial, particularly for wheat (*high agreement, robust evidence*). [7.4, Figures 7-5, 7-6, and 7-7]

Adaptation possibilities of food systems to climate change show a very wide range in effectiveness. Net benefits of adaptation will increase with increasing local mean temperature up to ~3°C local warming above preindustrial (*medium confidence*). Generally, adaptation leads to lower reductions in food production than in its absence with an overall crop yield difference in adaptation cases of about 15-20% over non-adaptation cases (*high agreement, medium evidence*), with more effective adaptation at higher latitudes (*medium agreement, limited evidence*), but with some adaptation options more effective than others. Benefits of adaptation are greater for wheat, rice, and maize in temperate rather than tropical regions [7.1, 7.3.2, 7.5, 7.6, Figures 7-5, 7-9]

Urban areas

Increasing concentration of populations, assets, and economic activities in the urban areas of almost all countries, irrespective of income level, will increase the concentration of climate-related risks for a large and growing proportion of the world's population (*medium confidence*, based on *high agreement, medium evidence*). Climate change will shift the comparative advantages of cities and regions and differentially threaten or enhance the resource, asset, and economic base and so lead to significant structural changes and impacts on local, national, and potentially the global economy. [8.1, 8.3, 8.4]

Rural areas

Future impacts on rural areas will be mediated in complex ways by changing patterns of extreme events and/or effects of climate change on agriculture and less-managed ecosystems (*high confidence*). Major impacts will be felt through impacts on water supply, food security, and agricultural incomes, including impacts on major non-food cash crops such as coffee. Adaptation can build on current responses to climate variability, in production of food crops, cash crops, and livestock and in water management, but these may not be sufficient to deal with the range of projected climate change. [9.3.3, 9.4.1, 9.4.3]

Climate change will lead to higher prices and increased volatility in agricultural markets, which may undermine global food supply security while differentially affecting net buyers and net sellers of food (*medium* to *high confidence*). Deepening agricultural markets through reforming trade and making institutional efforts to improve the predictability and reliability of the world trading system, as well as by investing in additional

supply capacity of small-scale farms in developing countries, could help reduce market volatility and manage food supply shortages that might be caused by climate change (*medium agreement*). [9.3.3]

Monetized impacts of climate change will be significant especially for the developing regions, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*high confidence*). Valuation of non-marketed ecosystem services and limitations of economic valuation models that aggregate across contexts pose challenges for valuing rural impacts. [9.3.4]

Key economic sectors and services

Climate change would reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*high agreement, robust evidence*). Energy demand will be influenced by changes in demographics, lifestyles, design and insulation of housing, and energy efficiency. [10.2]

Climate change would affect energy sources and technologies differently, depending on resources (water flow, wind, insolation), technological processes, or locations involved (*high agreement, robust evidence*). Changes in the availability and temperature of water for cooling are the main concern for thermal and nuclear power plants, but several options are available to cope with reduced water availability. Climate change would influence the integrity and reliability of pipelines and electricity grids (*medium agreement, medium evidence*). [10.2]

Human health

In the next few decades, climate change impacts on ill-health include the following (*high confidence*): greater incidence of injury, disease, and death due to more intense heat waves, storms, floods, and fires; increased risk of under-nutrition resulting from diminished food production in poor regions; loss of work capacity and reduced labor productivity in vulnerable populations; increased risks of food- and water-borne diseases and vector-borne infections; and modest improvements in some areas due to lower impacts of cold, shifts in food production, and reduction of disease-carrying vectors. The most effective adaptation measures for health in the immediate term are programs that extend basic public health measures and essential health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). [11.4, 11.5, 11.6, 11.7]

For global mean temperature increase of 4°C above 1986-2005, important limits to adaptation for health impacts may have been exceeded in many areas of the world (*high confidence*). These relate to sea-level rise, storms, loss of agricultural productivity, and daily temperature/humidity conditions that exceed coping mechanisms. See Box SPM.5. [11.8]

Human security

Climate change threatens human security, because it a) undermines livelihoods, b) compromises culture and identity, c) increases migration that people would rather have avoided, and d) undermines the ability of states to provide the conditions necessary for human security (*high agreement, robust evidence*). For populations that are already socially marginalized, are resource dependent, and have limited capital assets, human security may be progressively undermined as the climate changes. [12.1.2, 12.2, 12.3, 12.7]

Climate change will have significant impacts on forms of migration that compromise human security (*medium agreement, medium evidence*). Mobility is a widely used and often effective strategy to maintain livelihoods in response to social and environmental changes (*high agreement, medium evidence*). Legitimate and inclusive planning processes can help alleviate the conflict and insecurity that individuals and communities may experience from implementation of planned resettlement. [9.3.3, 12.3.2, 12.4.2, 12.4.3]

Climate change will lead to new challenges to states and will shape both conditions of security and national security policies (*medium agreement, medium evidence*). Some states are experiencing major challenges to their territorial integrity, including Arctic countries, small island states, and other states highly vulnerable to sea-level rise. Some impacts of climate change, such as changes in sea ice, transboundary and shared water resources, and migration of pelagic fish stocks, have the potential to increase rivalry among states. The presence of robust institutions can manage many of these rivalries such that human security is not severely eroded. [12.5.4, 12.6]

Livelihoods and poverty

Future impacts of weather events and climate will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas (*medium confidence,* based on *medium agreement, medium evidence*). Climate change will exacerbate multidimensional poverty in low and lower middle-income countries, including high mountain states and countries with indigenous people affected by sea-level rise and relocation, and create new poverty pockets in upper middle- to high-income countries. Urban and wage-labor dependent poor households, as well as regions with high food insecurity (above all in Africa) and high inequality, will be particularly affected due to food price increases. [10.9, 13.2.2, 13.4]

Social protection programs can help the chronically poor reduce risk and protect assets during crises, through transfers of income or assets to the poor, protection against livelihood risks, and enhancement of the social status and rights of the marginalized (*medium confidence*). Existing examples underscore the need to explicitly address livelihood security and resilience in the long-term, rather than focusing on short-term disaster relief. [13.4]

Regional risks

Examples of specific regional risks across sectors are presented in Table SPM.4. Figure SPM.5 provides a synthesis of sectoral risks for several regions, based on the expert judgment of assessment authors. Risks are estimated for the era of climate responsibility (here, for 2030-2040) and for the era of climate options (here, for 2080-2100) under different levels of global average warming (about +2 or +4°C global average warming above preindustrial in 2080-2100). Risks are summarized sector by sector, reflecting the overall structure of the WGII report (Part A).

[INSERT TABLE SPM.4 HERE
Table SPM.4: Examples of regional risks that increase with increasing level of climate change. Examples of potential positive impacts are also given. Risks increasing moderately or severely from now until the 2040s, which can be considered an era of climate responsibility, are described, in addition to risks increasing from ~2050 through the end of the 21st century, which can be considered to represent an era of climate options. For risks increasing in both the era of climate responsibility and the era of climate options, the potential for proactive adaptation to reduce the risks is characterized as low or high, with detail provided on adaptation issues and prospects. Risks increasing in the era of climate options can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options. Increasing risks in the era of climate responsibility are generally difficult to reduce substantially through mitigation, even with globally effective mitigation. They can be managed through vulnerability reduction, adaptation, and transformations that promote climate-resilient development pathways.]

[INSERT FIGURE SPM.5 HERE
Figure SPM.5: Estimated risk from climate change to selected sectors and systems in Africa (A), Europe (B), and North America (C), for different time frames (2030-2040 and 2080-2100), under two levels of global average warming above preindustrial (2°C and 4°C) and different assumptions about adaptation to manage these risks. Levels of risk and of adaptation are differentiated by colored shading, ranging from high adaptation to low adaptation. Estimated risks rely on expert judgments. The risk categories reflect the overall structure of Part A of the WGII AR5. [Figures 22-7 and 26-6]]

C.ii. Key and Emergent Risks

Key risks are potential adverse consequences for humans and social-ecological systems due to the interaction of climate-related physical hazards with vulnerabilities of societies and systems exposed. Risks are considered "key" due to high physical hazard or high vulnerability of societies and systems exposed, or both. [Box 19-2]

Key risks identified with *high confidence* include the following. [19.5.1, 19.6.2]

- Increased food insecurity from local conditions (e.g., adverse changes in rainfall patterns, limited alternative sources of income for some affected households) and regional and national conditions (e.g., breakdown of food distribution and storage processes).

- Dispossession of land, including alteration of rural inhabitants' coping and adaptation processes, from shifts in energy policies and global markets.
- Loss of livelihoods due to changes in climatic conditions and socioeconomic structures affecting people living in low-lying coastal zones and people engaged in rain-fed agriculture in developing and economies-in-transition countries.
- Increasing morbidity, mortality, and infrastructure failure as well as new systemic risks (e.g., risk of heat stress as a result of power shortages during extreme events) affecting urban areas in developed and developing countries.
- Increase in disease burden from the interaction of changes in physical climate conditions (e.g., increasing temperatures) with vulnerability (e.g., due to an aging population).
- Key risks associated with global mean temperature increase >4°C relative to preindustrial include exceedance of human physiological limits in some locations and nonlinear earth system responses. See Box SPM.5.

Interactions among climate change impacts in various sectors and regions, and human vulnerability and adaptation in other sectors and regions, as well as interactions between adaptation and mitigation actions present a variety of emergent risks (*high confidence*). [19.3.2]

- The risk of severe harm and loss due to climate-change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones. These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure.
- The risk of climate change to human systems is increased by loss of ecosystem services (e.g., water and air purification, protection from extreme weather events, preservation of soils, recycling of nutrients, pollination of crops), which are supported by biodiversity.
- In some water-stressed regions, groundwater stores that have historically acted as buffers against climate change impacts are being depleted, with adverse consequences for human systems and ecosystems, whilst at the same time climate change may directly increase or decrease regional groundwater resources.
- Climate change adversely affects human health, increasing exposure and vulnerability to other stresses, for example by altering prevalence and distribution of weather- and climate-sensitive diseases, increasing injuries and fatalities from extreme weather events, and eroding mental health following population displacement.
- Spatial convergence of impacts across sectors creates impact hotspots involving new interactions (Fig. SPM.6).

[INSERT FIGURE SPM.6 HERE
Figure SPM.6: Some salient examples of multi-impacts hotspots identified in this assessment. [Figure 19-2]]

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change, sometimes mediated by the adaptive responses of human populations (*high confidence*). [19.4.1, 19.4.2]

- Increasing prices of food commodities on the global market due to local climate impacts, sometimes in conjunction with demand for biofuels, decrease food security and exacerbate malnutrition in distant locations.
- Climate change will pose significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states.
- The possible effect of climate change on conflict and insecurity has the potential to become a key risk because the magnitude of the influence of climate variability on security reported in most studies is large.
- Shifting species ranges in response to climate change adversely affect ecosystem function and services while presenting new challenges to conservation efforts. Where range shifts cannot track climatic changes, species are at risk of eventual extinction.

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). Assessments of stringent mitigation scenarios suggest that they can potentially avoid one half of the aggregate economic impacts that would otherwise accrue by 2100, and between 20-60% of the physical impacts, depending on sector and region. [19.7.1, 19.7.2]

Table SPM.5 presents specific examples of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in the report. Box SPM.6 integrates expert judgments about risks under the reasons for concern framework.

[INSERT TABLE SPM.5 HERE

Table SPM.5: A selection of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in the report. The examples underscore the complexity of risks determined by various climatic hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, demographic changes, or tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climate-change-related harm and loss can occur. The examples illustrate that current global megatrends (e.g., climate change, urbanization, demographic changes), in combination and in specific development contexts (e.g., in low-lying coastal zones), can generate new systemic risks that go far beyond existing adaptation and risk management capacities, particularly in highly vulnerable regions. [Table 19-3]]

_____ START BOX SPM.5 HERE _____

Box SPM.5. Consequences of >4°C Temperature Increase

Projections of climate change impacts at 4°C global mean temperature increase above preindustrial indicate large impacts for physical, biological, and human systems and, in turn, large aggregate impacts for society and the global economy (*high confidence*). Global-mean surface temperatures for 2081–2100 (relative to early industrial, 1886–1905) for RCP 6.0 and 8.5 will *likely* be in the 5–95% range of the CMIP5 climate models, i.e., 2.0°C–3.9°C (RCP6.0), 3.3°C–5.5°C (RCP8.5).

For 4°C global mean temperature increase above preindustrial, the effects of climate change on water resources and ecosystems are projected to become dominant over other drivers such as population increases and land use change (*medium confidence*). Widespread coral reef mortality is projected (*high confidence*). Agricultural production is expected to decline in mid to high latitudes once local temperature rise exceeds 3°C (and for lower temperature rise in the tropics), corresponding to a global temperature rise below 4°C (*medium confidence*). Beyond 4°C there is high risk of marked yield loss even at high latitudes (*medium confidence*). Extreme heat waves such as that experienced in Russia in 2010 can become typical of a normal summer for a 4°C increase (*high confidence*). Sea-level rise in a 4°C world could result in the inundation of many small island states (*high confidence*). Emerging risks include exceedance of human physiological limits in some areas for a global temperature rise of 7°C (*medium confidence*).

Sub-Saharan Africa is identified as a multi-impacts hotspot in a 4°C world, with risks of increases in hunger and disease, and of loss of ecosystem function (*high confidence*). A 4°C increase would be expected to result in non-linear earth system responses, such as (1) eventual, irreversible loss of the Greenland Ice Sheet (*high confidence*) and (2) terrestrial carbon loss due to climate-carbon cycle feedback releasing CO_2 or CH_4 (*very likely*), which would accelerate climate change further. There would also be an increased chance of triggering the collapse of the West Antarctic Ice Sheet.

[12.4, 12.5, 19.4.3, 19.5.1, 19.6.3, 19.7.5, 23.4.1, WGI AR5 SPM, 2.4.3, 8.5.3, 12.4.1, Chapter 6, Table 13.5]

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Box SPM.6. Anthropogenic Interference with the Climate System

Anthropogenic interference with the climate system is occurring. [WGI AR5 SPM, 10.3-10.6] The impacts of climate change[1] are already widespread and consequential. [18.3-18.6] Determining whether anthropogenic interference is dangerous involves judgments about risks.

The IPCC assesses scientific and technical understanding of risks and the range of possible outcomes. It also assesses understanding of how risks are perceived, as well as methods for incorporating different value systems in decisionmaking. The IPCC cannot, however, make a determination of the level of anthropogenic interference that is dangerous.

[INSERT FOOTNOTE 1: See Box SPM.1 for description of differing usage of the term “climate change” in IPCC and UNFCCC.]

Assessment of existing frameworks pertinent to Article 2 of the UNFCCC has led to evaluations of risk being updated in light of the advances since AR4, including SREX and the current report's discussions of vulnerability, human security, and adaptation. The management of key and emergent risks of climate change and reasons for concern includes (i) mitigation that reduces the likelihood of physical impacts and (ii) adaptation that reduces the vulnerability and exposure of societies and ecosystems to those impacts. Many of the key vulnerabilities, key risks, and emergent risks identified in this report reflect differential vulnerability between groups due to, for example, age, wealth, or income status, and deficiencies in governance, which are particularly important in assessing risk from extreme events and risk associated with the distribution of impacts. [19.6.1, 19.6.3, 19.7]

Impacts of climate change have now been documented globally, covering all continents and the ocean (*high confidence*; Table SPM.1). The degree to which projected damages are now manifest, or the detection of stronger early warning signals for expected impacts, can contribute to a more comprehensive risk assessment for dangerous anthropogenic interference with the climate system. [18.6.2]

Updating of the reasons for concern (Box SPM.6 Figure 1) leads to the following assessment:

- Unique human and natural systems tend to have very limited adaptive capacity, and hence climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C over preindustrial levels were exceeded (*high confidence*). [18.6.2, 19.6.3]
- The overall risk from extreme events due to climate change has not changed significantly since AR4, but there is higher confidence in the attribution of some types of extreme events to human activity and in the assessment of the risk from extreme events in the coming decades. In addition, there is a new appreciation for the importance of exposure and vulnerability, in both developed and developing countries, in assessing risk associated with extreme events. [18.6.2, 19.6.1, 19.6.3]
- Risk associated with the distribution of impacts is generally greatest in low-latitude, less developed areas, but because vulnerability is unevenly distributed within countries, some populations in developed countries are highly vulnerable to warming of less than 2°C, as noted in AR4 (*high confidence*). [19.6.3]
- Globally aggregated risk is underestimated because it does not include many non-monetized impacts, such as biodiversity loss, and because it omits many known impacts that have only recently been quantified, such as reduced labor productivity (*high confidence*). In addition, aggregated estimates of costs mask significant differences in impacts across sectors, regions, and populations (*very high confidence*). The overall assessment of aggregate risk and confidence in that assessment has not changed since AR4. [19.6.3]
- The risk associated with large-scale singular events such as at least partial deglaciation of the Greenland ice sheet remains comparable to that assessed in AR4. [19.6.3]

[INSERT BOX SPM.6 FIGURE 1 HERE
Box SPM.6 Figure 1: The dependence of risk associated with reasons for concern (RFCs) about climate change, updated based on expert judgment in this assessment. The color scheme indicates the additional risk due to climate change (with white to purple indicating the lowest to highest level of risk, respectively). Purple color, introduced here for the first time, reflects the assessment that unique human and natural systems tend to have very limited adaptive capacity. [Figure 19-5]]

_____ END BOX SPM.6 HERE _____

D) BUILDING RESILIENCE THROUGH MITIGATION, ADAPTATION, AND SUSTAINABLE DEVELOPMENT

D.i. Climate-resilient Pathways and Transformation

Climate-resilient pathways for development are rooted in iterative processes. These processes identify vulnerabilities to climate change impacts and take appropriate steps to reduce vulnerabilities in the context of development needs and resources and to increase the options available for vulnerability reduction and coping with surprises. They involve monitoring emerging climate parameters and their implications, along with the effectiveness of vulnerability reduction efforts, and revising risk reduction responses on the basis of continuing learning. [20.2.3, 20.6.2]

Climate-resilient pathways include actions across scales (a) to reduce climate change and its impacts and (b) to assure that effective risk management and adaptation can be implemented and sustained (*high confidence* based on *high agreement, medium evidence*). Impacts of climate change avoided under a range of scenarios for mitigation of greenhouse gas emissions are potentially large and increasing over the 21st century. Since mitigation reduces the rate as well as the magnitude of warming, it also delays the need to adapt to a particular level of climate change impacts, potentially by several decades. Prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation. Achieving climate-resilient development pathways benefits from attention to dynamic livelihoods, multidimensional poverty, and multifaceted impacts of climate change and climate change responses. [2.3, 2.4, 13.4, 19.7.1, 20.2, 20.3, 20.4, 20.6.1]

Estimates of global adaptation costs continue to improve but remain inconsistent in methods, sectoral coverage, purposes, and time frames. The most recent estimates suggest a range from 75 to 100 US$ billion per year globally by 2050 (*low confidence*). Important omissions from these estimates suggest the high end of this range could be much higher, and important shortcomings in the data and methods available for costing adaptation suggest the low end of this range could be substantially lower. Existing estimates of global adaptation costs could be higher if sectors such as ecosystems and tourism and socially contingent effects were included, and if developing countries' adaptation deficits were more fully taken into account. [17.3.6, 17.3.10, 17.3.11, 17.6]

Avoiding limits to adaptation will necessitate policy responses and awareness that go beyond greenhouse gas mitigation and adaptation responses alone (*medium agreement, limited evidence*). Climate-resilient pathways will often require transformations in order to assure sustainable development (*high confidence*, based on *high agreement, medium evidence*). See Box SPM.7. [2.2, 16.4, 16.6, 16.7, 20.5]

D.ii. Examples of Co-benefits, Synergies, and Tradeoffs

Responses to the risks of climate change can have implications beyond their primary objectives for the resilience of societies and systems.

Adaptation designed for one sector may interfere with the functioning of another sector, creating new risks (*high confidence*). Table SPM.6 presents potential tradeoffs among adaptation objectives. [4.3, 17.3, 19.3.2]

[INSERT TABLE SPM.6 HERE
Table SPM.6: Examples of potential tradeoffs among adaptation objectives. [Table 16-2]]

Use of the terrestrial biosphere in climate mitigation actions, such as through introduction of fast-growing tree species for carbon sequestration or the conversion of forest to biofuel plantations, may lead to negative impacts on ecosystems and biodiversity (*very high confidence*). Climate policies, such as encouraging cultivation of biofuels and payments under REDD, will result in mixed and potentially detrimental impacts on land-use and on the livelihoods of poor and marginalized people (*medium confidence*). Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (e.g., purposeful nutrient fertilization, direct CO_2 injection into the deep ocean) have very large associated environmental and social consequences (*high confidence*). [3.7.2, 4.2.4, 6.4.2, 9.3.3, 13.3, 13.4, 21.5.3]

Reducing emissions of climate-altering pollutants can help reduce health impacts of climate change and simultaneously have local health co-benefits, for instance by reducing local emissions of health-damaging and climate-altering air pollutants associated with energy production and use in households and communities (*very high confidence*). In Asia as an example, development of sustainable cities with low-emissions vehicles and more trees and greenery would have a number of co-benefits including for public health. [11.9, 24.4-7]

In Europe, there are opportunities for policies that improve adaptive capacity and also help meet mitigation targets (*high confidence*). For example, some agricultural practices can potentially mitigate GHG emissions and at the same time adapt crops to increase resilience to temperature and rainfall variability. [23.8]

For Australasia, significant synergies and tradeoffs exist between mitigation and adaptation responses; interactions occur both within Australasia and between Australasia and the rest of the world (*very high confidence*). Flow-on effects from climate change impacts and responses outside Australasia have the potential to

outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*), but they remain amongst the least explored issues. [25.7.5, 25.9, Box 25-10]

Throughout North America, adaptation actions at the local level have the potential to result in synergies, conflicts, or tradeoffs with mitigation and other development actions and goals (*high confidence*). For example, reductions in emissions of greenhouse gases can yield health co-benefits, while sea walls can protect coastal properties yet may negatively affect the structure and function of coastal ecosystems. [26.8]

For small islands, energy supply and use, tourism infrastructure and activities, and coastal wetlands offer opportunities for adaptation-mitigation synergies (*medium confidence*). [29.6.2, 29.7.2, 29.8, 29.3.3]

_____ START BOX SPM.7 HERE _____

Box SPM.7. Adaptation Limits and Transformation

Limits to adaptation emerge from the interaction between climate change and biophysical and socioeconomic constraints (*high agreement, robust evidence*). See Box SPM.7 Figure 1. Some adaptation limits may be removed over time through changing values or technological advancement.

[INSERT BOX SPM.7 FIGURE 1 HERE
Box SPM.7 Figure 1: Conceptual model of acceptable, tolerable, and intolerable risks and implications for limits to adaptation. [16.2, Figure 16-1]]

Greater adaptation efforts will be required to achieve objectives if mitigation efforts are not successful in avoiding high magnitudes of climate change (*high agreement, limited evidence*). There are, however, limits to the extent to which adaptation could reduce the impacts not avoided by mitigation, and residual loss and damage may occur despite adaptive action. The greater the magnitude of climate change, the greater the likelihood that adaptation will encounter limits.

Transformative changes may be necessary as a response to projected climate changes (*medium confidence*). Transformation in wider political, economic, and social systems can open or close policy spaces for more resilient and sustainable forms of climate responses (*high confidence*). While transformations may be reactive, forced, or induced by random factors, they may also be deliberately created. Deliberate transformations can take place in relation to transformational adaptation, transformation to low-carbon societies, or transformations to global sustainability.

[14.1, 14.3.4, 16.2, 16.3, 16.4, 16.5, 19.6, 19.7, 20.5, 25.3, 25.4, 25.11]

_____ END BOX SPM.7 HERE _____

Table SPM.1: Observed impacts attributed to climate change with *medium* (*) or *high* (**) confidence, for physical, biological, and human systems across eight major world regions. [Tables 18-6, 18-7, 18-8, 18-9]

REGION	Freshwater Resources & Systems	Terrestrial Ecosystems, Drought, & Wildfire	Coastal & Marine Systems	Human Systems
Africa	Retreat of tropical highland glaciers in East Africa* Lake surface warming & water column stratification increases in the Great Lakes & Lake Kariba** [13.2.1, 22.3.2, 22.5.1]	Tree density decreases in Sahel & semi-arid Morocco* Climate-driven range shifts of several southern plants & animals* Increased drought in the Sahel since 1970, partially wetter conditions since 1990* [22.2.2, 22.3.2]		Decline in fruit-bearing trees in Sahel*
Europe	Retreating glaciers in the Alps** Increase in rock slope failures in Western Alps** [18.3.1]	Earlier greening, earlier leaf emergence, & fruiting in temperate & boreal trees** Increased colonization of alien plant species in Europe* Earlier arrival of migratory birds in Europe since 1970* Increasing burnt forest areas during recent decades** [4.2.4, 4.4.1]	Poleward shifts in the distributions of zooplankton, fishes, seabirds, & benthic invertebrates, & conversion of polar into more temperate & temperate into more subtropical system characteristics in Northeast Atlantic** Phenology changes & retreat of colder water plankton to north in the Northeast Atlantic, with mean poleward movement of plankton reaching up to 200–250 km per decade from 1958–2005* Atlantic cod distribution shift due to warming, interacting with regime shift & regional changes in plankton phenology in North Sea.* Decreasing abundance of eelpout in Wadden Sea** [6.3.2, Table 6-8, Figure 6-16, 18.3.3, 30.5.1]	Stagnation of wheat yields in some countries in recent decades, due to warming and/or drought*
Asia	Permafrost degradation in Siberia, Central Asia, & Tibetan Plateau** Shrinking mountain glaciers across Asia.* Increased runoff in many rivers due to shrinking glaciers in the Himalayas & Central Asia** Surface water degradation in parts of Asia partially related to climate change* Earlier timing of maximum spring flood in Russian rivers** [Box 3-1, Box 3-2, 24.4.1, 28.2.1, WGI AR5 Chapter 4.3.2-4.3.3, 10.5.3]	Changes in plant phenology & growth in many parts of Asia, particularly in the north & east* Distribution shifts of many plant & animal species, particularly in the north of Asia, generally upwards in elevation or polewards* Advance of shrubs into the Siberian tundra* [4.2.1, Box 4-1, 24.4.2, 28.2.3]	Decline in coral reefs & large seaweeds in tropical Asian & Japanese waters** Shift from sardines to anchovies in Japanese Sea* [6.3.2, Figure 16-6, 24.4.3]	
Australasia	Significant decline in late-season snow depth at four alpine sites in Australia (1957-2002)*	Climate-related changes in genetics, growth distribution, & phenology of many species (e.g., earlier emergence of butterflies, change in plant flowering dates & bird breeding times, decline in body size of passerine birds)* [Table 25-3]	Mass bleaching of corals in the Great Barrier Reef, changes in coral calcification rates, & changes in coral disease dynamics** Multiple impacts of climate change on marine ecosystems from warming oceans, although other environmental changes may play a role. Examples are growth rate increases in fishes, intertidal-invertebrate range shifts, range shifts in near-shore fishes related to kelp decline, increasing abundance of northern marine species in Tasmania, recruitment declines of rock lobster & abalone, declines in growth rate & biomass of phytoplankton, southward expansion of some tropical seabirds in Australia** [6.3.2, Box 18-3, 25.6.2, Table 25-3]	Wine-grape maturation has advanced in recent decades, partly due to warming*

REGION	Freshwater Resources & Systems	Terrestrial Ecosystems, Drought, & Wildfire	Coastal & Marine Systems	Human Systems
North America	Primarily decreasing trends in amount of water stored in spring snowpack from 1960-2002** Observed shift to earlier peak flow in snow dominated rivers in Western North America** Runoff increases in the Midwestern & Northwestern US, decreases in Southern states* [26.2.2, WGI AR5 Chapter 2.6.2]	Species distribution shifts upward in elevation & northward in latitude across multiple taxa* Phenology changes* Increases in wildfire activity, including fire frequency & duration, length of fire season, & area burned* [26.4.1, 26.4.2, Box 26-2]	Northward range shifts of Northwest Atlantic fishes in response to warming since the 1960s, with some of the shifts being correlated with the Atlantic Multidecadal Oscillation* Earlier onset of Pink Salmon migration (Alaska), collapse of Sockeye Salmon spawning migration (Fraser River, BC), due to warming** Loss of biomass of midwater fishes off California Coast** [6.3.3, 6.6.3, Table 6-8, Figure 6-16]	Direct & indirect economic impacts of climate extremes on industry through reduced supply of raw material, the production process, the transportation of goods, & the demand for certain products* [26.8]
Central & South America	Retreat of tropical Andean glaciers in Venezuela, Colombia, Ecuador, Peru, & Bolivia (1950-2000) & glaciers & ice-fields in the extra tropical Andes** Changes in extreme flows in Amazon River* Changed discharge patterns in rivers in the Western Andes due to retreating glaciers & reduced snowpack; for major river basins in Colombia, decreased discharge during the last 30-40 years** Increased stream flow in sub-basins of the La Plata River, attributed to increasing precipitation, but also to trends in land-use changes that have reduced evapotranspiration** [27.2.1, 27.3.1]		Bleaching of coral reefs in the western Caribbean near the coast of Central America** [27.3.3]	Increase in frequency & extension of malaria* Increase in agricultural yields in Southeastern South America* [27.3.4, 27.3.7]
Polar Regions	Decreasing Arctic sea ice cover in summer & reduction in glacier ice volume, due to warming* Decreasing snow cover duration across the entire Arctic* Widespread permafrost degradation, especially in the southern Arctic** Rising winter minimum flows in most sectors of the Arctic due to enhanced groundwater input due to permafrost thawing* Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes being created in areas of formerly frozen peat** [28.2.1, 28.2.3, WGI AR5 Chapter 10.5.1]	Increase in shrub cover in tundra in North America & Eurasia.** Significant advance of Arctic tree-line in latitude & altitude, due to warming, although lower pace than expected due to insect outbreaks & land-use history. Changes in breeding area & population size of subarctic birds, due to warming & shrub encroachment in the tundra* Retreating snow-bed ecosystems & tussock tundra, due to prolonged thawing season & less precipitation in the form of snow.** Increasing occurrence of ice layers in the annual snow pack due to rain-on-snow events, affecting animal populations in the tundra* Increasing plant species in the West Antarctic Peninsula & nearby islands over the past 50 years** Increasing drought in high Arctic polar deserts** Increased frequency of wildfires in conifer forest at Arctic southern fringe, due to increasing summer temperature. Tundra wildfires are increasing in frequency in the Low Arctic, due to increasing summer air temperature & subsequent surface drought* [28.2.1, 28.2.3]	Sea ice loss negatively affecting many arctic & subarctic marine non-migratory mammals (walrus, seals, whales)** Reduced growth rate & body mass, lower survival & reproductive capacity of polar bears, linked to reduced off-shore range & sea-ice loss due to warming** Reduced reproductive success of Arctic seabirds, due to earlier sea-ice break-up* Reduced thickness of foraminifera shells due to acidification of Southern Ocean waters * Declines in Antarctic krill density in the Scotia Sea by ~30% since the 1980s, due to reduced winter sea ice extent & duration* Many Southern Ocean species of seals & seabirds, e.g., penguins & albatross, negatively responding to warmer conditions* Increased coastal erosion in Arctic, due to prolonged ice-free season at shore, increased exposure to wave activity, & degrading permafrost** [6.3.4, 28.2.2, 28.2.4, 28.2.5, 28.3.4]	Impact on livelihoods of Arctic indigenous peoples* [18.4.5, Box 18-5]
Small Islands		Tropical-bird population changes in Mauritius, due to changes in rainfall* [29.3.2]	Coral bleaching near many tropical small islands** [29.3.1]	

Table SPM.2: Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.

Mangrove restoration to reduce flood risks and protect shorelines from storm surge
EXPOSURE AND VULNERABILITY: Loss of mangroves increases exposure of coastlines to storm surge, wave erosion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, are particularly vulnerable. [15.3.4, 29.7.2]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: *Likely* increase in extreme sea levels since 1970, mainly caused by rising mean sea level. *Low confidence* that any reported long-term changes in tropical cyclones are robust. Projected: By the end of the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in some basins. [WGI AR5 2.6.3, 3.7.5, 11.3.2, Box 14.2]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: Regional rates of sea level change can vary significantly from the global mean. Mean significant wave height *likely* increased since the mid-1980s over much of the mid-latitude North Atlantic, the North Pacific, and the Southern Ocean. For tropical cyclones observed over the satellite era, increases in the intensity of the strongest storms in the Atlantic appear robust. Projected: For all ocean basins, tropical cyclone frequency is projected to decline or remain the same, the mean lifetime maximum intensity of tropical cyclones is projected to increase or remain the same, and cyclone-associated rainfall rates are projected to increase. In the North Atlantic and the eastern part of the North Pacific, the frequency of category 4/5 tropical cyclones is projected to increase. *Very likely* increase in the occurrence of future extreme sea level and related coastal flooding events with increasing global mean sea level, but *low confidence* in region-specific projections in storminess and storm surges. [WGI AR5 2.6.3, 3.4, 3.7, 13.7.2; Figures 3.6-3.8, 13.19; Box 14.2]
DESCRIPTION: Mangrove restoration and rehabilitation has occurred in a number of locations (Vietnam, Myanmar, Samoa, and Brazil, for example) to reduce coastal flooding risks and protect shorelines from storm surge. In Vietnam, restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion. [8.3.3, 2.3.4, 15.3.4, 27.3.3, 22.4.5]
BROADER CONTEXT: •Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, wave damage, and erosion. •Synergies with mitigation given that mangrove forests are sinks for carbon. •Restoration and rehabilitation can help build local knowledge, capacity, and strategies to institutionalize climate change adaptation and resilience in local planning and development. •Mangrove bioshields created from exotic species can detrimentally impact native ecosystems. [8.4.2, Box 5.4, 29.7.2, 15.3.4]
Farming practices in Africa, such as zai and integration of trees into annual cropping systems
EXPOSURE AND VULNERABILITY: Land degradation and soil infertility have negatively impacted yields in parts of Africa, such as in Zambia, Malawi, the highlands of Ethiopia, Burkina Faso, and the drylands of the Sahel. Soil erosion, soil compaction due to livestock trampling, and low soil water holding capacity reduce plant growth. [7.5.2, Table 9-6, Box 22-4]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: Increase in globally averaged near surface temperatures since 1900, with warming particularly marked since the 1970s. *Very likely* decrease in the overall number of cold days and nights and increase in the overall number of warm days and nights, on the global scale between 1951 and 2010. *Medium confidence* that the length of warm spells, including heat waves, has increased globally since 1950. *Medium confidence* in global precipitation change over land since 1950. *Likely* increase in the number of heavy precipitation events in more regions than the number has decreased since 1950. *Low confidence* in any observed large-scale trends in drought. Projected: For RCP 4.5, 6.0, and 8.5, global mean surface air temperatures are projected to at least *likely* exceed 2°C with respect to preindustrial by 2100. *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global temperature increases, for events defined as extremes on both daily and seasonal timescales. *Virtually certain* increase in global precipitation as global mean surface temperature increases. Regional to global-scale projections of soil moisture and drought remain relatively uncertain. For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 2.4, 2.5.1, 2.6.1, 2.6.2, 12.3.1, 12.4.1, 12.4.3, 12.4.5; Figures 2.28, 12.2, 12.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:

Observed: Increase in frequency of warm days and nights in northern and southern part of continent and decrease in frequency of cold days and nights in southern part of continent.
Overall increase in dryness and modest increases in rainfall over most of equatorial Africa and the Red Sea coast (*medium confidence*).
Projected: *Likely* increase in warm days and decrease in cold days in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*).
Likely more frequent and/or longer heat waves and warm spells in Africa (*high confidence*).
[22.2.2; SREX Tables 3-2, 3-3]

DESCRIPTION:

Zai uses small pits dug manually during the dry season, combined with contour stone bunds to slow runoff. Animal manure or compost is placed in each pit. The pits facilitate water infiltration and concentrate runoff water, and the applied organic matter improves soil nutrient status and attracts termites, which positively affect soil structure. The practice can also improve tree growth amid crop rows, and trees, especially nitrogen-fixing varieties, can be integrated as an independent strategy. Trees reduce crop exposure to wind and heavy rainfall and improve moisture retention and rainwater capture. Factors that have enabled farmer-managed natural regeneration include in southern Niger devolving tree ownership from the state to the farmer, as well as community-based efforts involving partnerships of farmers and NGOs.
[7.5.2, Table 9-6, Box 22-4, 15.3.4]

BROADER CONTEXT:

- Both techniques can improve yields, water retention, food security, and income generation, also reversing land degradation.
- Tree growth, through production of fruit, animal fodder, or fuelwood, can expand livelihood options and allow diversification, thereby enhancing resilience.
- Zai is a very labor-intensive technique, which can be expedited through use of animal-drawn implements.
- Farmer-managed natural regeneration has been paired with other low-cost behavioral actions, for example in Ethiopia, aiming to reverse ecosystem degradation and promote reforestation with benefits for carbon sequestration.

[7.5.2, Table 9-6, Box 22-4, 15.3.4, 17.4.1]

Adaptive approaches to flood defense in Europe

EXPOSURE AND VULNERABILITY:

In some countries, a high percentage of the population is exposed to flooding. Exposed assets and infrastructure represent a substantial fraction of national GDPs.
[Box 5-3]

CLIMATE INFORMATION AT THE GLOBAL SCALE:

Observed: *Likely* increase in extreme sea levels since 1970, mainly caused by rising mean sea level.
Likely increase in the number of heavy precipitation events in more regions than the number has decreased since 1950.
Projected: *Very likely* that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971-2010 for all RCP scenarios.
For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms.
[WGI AR5 2.6.2, 3.7.5, 12.4.5, 13.5.1, Table 13.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:

Observed: Increased heavy wintertime precipitation since the 1950s in some areas of Northern Europe (*medium confidence*).
Increased heavy precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*).
Isostasy and decreasing sea level in Scandinavia.
Projected: Overall precipitation increase in Northern Europe and decrease in Southern Europe (*medium confidence*).
Increased extreme precipitation in Northern and Atlantic regions of Europe during all seasons, and in Central Europe except in summer (*high confidence*). Annual increases of intense precipitation days over the Mediterranean region.
Storm activity over the North Atlantic *likely* to increase and extend farther downstream into Europe, and to decrease on both the north and south flanks, especially over the Mediterranean (*medium confidence*).
Likely reduction in the occurrence of Northern Hemisphere extratropical storms, although the most intense storms reaching Europe *likely* to increase in strength. An increase in the North Atlantic Oscillation *likely* to increase the number of wintertime storms heading into Northern Europe and the average intensity of precipitation per storm.
[23.2.2; WGI AR5 Box 14.3; SREX Table 3-2]

DESCRIPTION:

Several governments have made ambitious efforts to address flood risk over the coming century. In the Netherlands, government recommendations include "soft" measures preserving land from development to accommodate increased river inundation; raising the level of lakes to ensure continuous freshwater supply; restoring natural estuary and tidal regimes; maintaining flood protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. The plan is estimated to cost €2.5 to 3.1 billion a year through 2050, 0.5% of the current Dutch annual GNP. The British government has also developed extensive adaptation plans to adjust and improve flood defenses for the protection of the Thames estuary and the city of London from future storm surges and river flooding. Pathways for different adaptation options and decisions depending on eventual sea level rise have been analyzed.
[Box 5-3, 23.7.1]

BROADER CONTEXT:

- The Dutch plan is considered a paradigm shift, addressing coastal protection by "working with nature" and providing "room for river." The concept of creating space for water and integrating water management approaches with goals of environmental protection is an essential component of integrated water management.
- The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise.
- The large infrastructure project of the Thames flood defense barrier involved public-private partnerships.
- In cities in Europe and elsewhere, the importance of having strong political leadership or government champions to drive the initial development of climate adaptation plans has been noted.

[Box 5.3, 23.7.1, 17.5.3, 8.5.3, 23.7.4, 23.7.2]

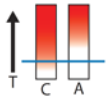
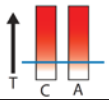
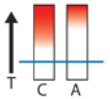
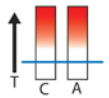
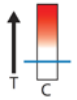
Relocation of agricultural industries in Australia
EXPOSURE AND VULNERABILITY: Crops sensitive to changing patterns of rainfall, water availability, and temperature. [7.5.2]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: Increase in globally averaged near surface temperatures since 1900, with warming particularly marked since the 1970s. *Very likely* decrease in the overall number of cold days and nights and increase in the overall number of warm days and nights, on the global scale between 1951 and 2010. *Medium confidence* that the length of warm spells, including heat waves, has increased globally since 1950. *Medium confidence* in global precipitation change over land since 1950. *Likely* increase in the number of heavy precipitation events in more regions than the number has decreased since 1950. *Low confidence* in any observed large-scale trends in drought. Projected: For RCP 4.5, 6.0, and 8.5, global mean surface air temperatures are projected to at least *likely* exceed 2° C with respect to preindustrial by 2100. *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global temperature increases, for events defined as extremes on both daily and seasonal timescales. *Virtually certain* increase in global precipitation as global mean surface temperature increases. Regional to global-scale projections of soil moisture and drought remain relatively uncertain. For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 2.4, 2.5.1, Figure 2.28, 2.6.1, 2.6.2, 12.3.1, 12.4.1, Figure 12.2, Figure 12.5, 12.4.3, 12.4.5]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: Mean temperature increase of 0.9°C per decade over Australia since 1911 (*very high confidence*). Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand (*high confidence*). Late autumn/winter decreases in precipitation in Southwestern Australia since the 1970s and Southeastern Australia since the mid-1990s, and annual increases in precipitation in Northwestern Australia since the 1950s (*very high confidence*). Significant increases in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). Projected: Further warming of Australasia this century *virtually certain*, greatest over inland areas and least in coastal areas. Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). Annual decline in precipitation over southwestern Australia (*high confidence*) and in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). Increase in intensity of rare daily rainfall extremes (*high confidence*) and of annual daily extremes (*medium confidence*) in Australia and New Zealand. Drought occurrence to increase in Southern Australia (*high confidence*). Snow depth and snow area to decline in Australia (*very high confidence*). Freshwater resources projected to decline in the highly populated southeast and the far southwest of Australia. [25.5.1, Table 25-1]
DESCRIPTION: Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use in situ in response to recent climate change or perceptions of future change. There have been new investments in grapes in Tasmania and switching from grazing to cropping in South Australia. Adaptive movement of crops has also occurred elsewhere, such as in China. [7.5.2, Table 9-6, 25.7.2, Box 25-5]
BROADER CONTEXT: •Considered transformational adaptation in response to impacts of climate change. •Positive or negative implications for communities in origin and destination regions, with substantial changes required in transport chains, inputs, management, or growing contracts. •Some decisions run across scales and include many stakeholders, with comprehensive regional assessments across enterprises and economic and resource outcomes needed. [7.5.2, 25.7.2, Box 25-5]

Table SPM.3: Entry points, strategies, measures, and options for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples given can be relevant to more than one category.

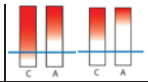
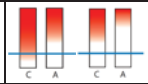
Entry Point	Category			Examples	Chapter Reference(s)
Vulnerability reduction through development and planning	Forms of sectoral integration	Human development	Specific measures	Low regrets options to reduce structural inequalities: improved access to education, nutrition, health facilities, energy, safe settlement structures, social support structures; reduced gender inequality and marginalization in other forms.	13.1.2, 13.3.1, 13.4.1, 13.4.2, 22.3.1
		Poverty alleviation		Insurance schemes, social protection programs, disaster risk reduction. Improved access to and control of local resources, land tenure, and storage facilities. Low regrets options to reduce structural inequalities.	13.1.2, 13.3.1, 13.3.2, 13.4.1
		Livelihood security		Income and asset diversification. Improved infrastructure. Access to technology and decision-making fora, enhanced agency.	13.1.1, 13.3.1, 13.4.1
		Disaster risk reduction and management		Early warning systems.	11.7.3, 22.4.5, 26.9.1
		Ecosystem management		Maintaining wetlands and urban green spaces, coastal afforestation.	8.3.3, Box 8.1, 15.3.1, Box CC-EA
		Spatial or land-use planning		Provisioning of adequate housing, infrastructure, and services. Managing development in flood prone and other high risk areas.	8.1.4, 8.4.3, 8.5.3
Adaptation	Structural/ concrete	Engineered	Specific options	Sea walls, water storage, improved drainage, beach nourishment, flood shelters. Improved infrastructure.	14.3.1, Table 14-2
		Technological		New crop and animal varieties, efficient irrigation and water use, hazard mapping and monitoring, early warning systems, home insulation.	14.3.1, Table 14-2
		Ecosystem-based		Wetland reestablishment, reestablishment of floodplains, bushfire fuel-reduction actions.	14.3.1, Table 14-2
		Services		Social safety nets, food banks, vaccination programs, municipal services.	14.3.1, Table 14-2
	Institutional	Economic		Financial incentives, insurance and other risk spreading.	13.3.2, 14.3.2, Table 14-2
		Laws and regulations		Land zoning laws, building standards, easements.	14.3.2, Table 14-2
		Government policies and programs		National and local adaptation plans, urban upgrading programs, municipal water conservation programs, disaster planning and preparedness.	14.3.2, Table 14-2
	Social	Educational		Awareness raising, extension services.	14.3.3, Table 14.2
		Informational		Hazard mapping and monitoring, early warning, community support groups.	14.3.3, Table 14-2
		Behavioral		Household preparation, evacuation planning, retreat and migration, water conservation, storm drain clearance.	14.3.3, Table 14-2
Transformation	Spheres of change	Practical	Specific strategies	Social and technical innovations, behavioral shifts, or institutional and managerial changes that produce measurable outcomes.	20.5.2
		Political		Changes in the political, social, cultural, and ecological systems or structures that currently contribute to risk and vulnerability or impede practical transformations.	20.5.2
		Personal		Changes in individual and collective assumptions, beliefs, values, and worldviews that influence climate change responses.	20.5.2
Mitigation	See WGIII AR5.				

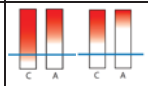
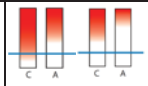
Table SPM.4: Examples of regional risks that increase with increasing level of climate change. Examples of potential positive impacts are also given. Risks increasing moderately or severely from now until the 2040s, which can be considered an era of climate responsibility, are described, in addition to risks increasing from ~2050 through the end of the 21st century, which can be considered to represent an era of climate options. For risks increasing in both the era of climate responsibility and the era of climate options, the potential for proactive adaptation to reduce the risks is characterized as low or high, with detail provided on adaptation issues and prospects. Risks increasing in the era of climate options can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options. Increasing risks in the era of climate responsibility are generally difficult to reduce substantially through mitigation, even with globally effective mitigation. They can be managed through vulnerability reduction, adaptation, and transformations that promote climate-resilient development pathways.

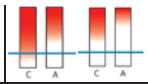
---------- LEGEND ----------

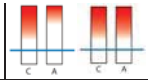
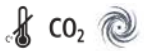
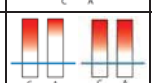
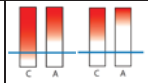
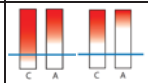
ERA & ADAPTATION POTENTIAL	**Risk for current (C) and hypothetical fully adapted (A) state. Color scheme depicts the additional risk due to climate change. White to red indicates lower and higher levels of risk, respectively. The vertical axis of each bar represents the level of climate change (T). The horizontal blue line indicates the level of climate change at the end of the era of climate responsibility.**	
	A risk increasing moderately as early as the era of climate responsibility (now through the 2040s), which can be reduced substantially with proactive adaptation.	 A risk increasing moderately as early as the era of climate responsibility (now through the 2040s), which will be difficult to reduce substantially even with proactive adaptation.
	A risk increasing moderately or severely during the era of climate options (~2050 through the end of the 21st century), which can be reduced substantially with proactive adaptation. The risk can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options.	 A risk increasing moderately or severely during the era of climate options (~2050 through the end of the 21st century), which will be difficult to reduce substantially even with proactive adaptation. The risk can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options.
	A risk increasing moderately as early as the era of climate responsibility (now through the 2040s), for which potential for risk reduction via proactive adaptation was not assessed.	 A risk increasing moderately or severely during the era of climate options (~2050 through the end of the 21st century), for which potential for risk reduction via proactive adaptation was not assessed.

CLIMATE DRIVERS	**Where particular climate driver(s) are especially relevant for an assessed risk, they are indicated via the symbols below.**							
	Average temperature		Extreme temperature		Precipitation		Extreme precipitation
CO_2	CO_2 concentration & ocean acidification		Damaging cyclone		Snow cover		Sea level

REGION	RISKS — FRESHWATER RESOURCES AND SYSTEMS	Climate Driver(s)	Era & Adaptation Potential	Adaptation Issues/Prospects	Chap. Ref.
Europe	Climate change is *likely* to further increase coastal and river flood risk and, if unabated, will substantially increase flood damages (monetary losses and people affected).			Adaptation can prevent most of the projected damages (*high confidence*).	23.3.1, 23.5.1, 23.7.1, 23.8.3
Asia	Shrinking of glaciers in Central Asia and the Himalayas is projected to affect water resources in downstream river catchments. Population growth and increasing demand arising from higher standards of living could worsen water security in many parts of Asia and affect many people in the future.			Water saving technologies and changing to drought tolerant crops have been found to be successful adaptation options in the region.	24.4.1, 24.9.3
Austral-asia	Systematic constraints on water resource use in southern Australia, driven by rising temperatures and reduced cool-season rainfall (*high confidence*).			Integrated responses encompassing management of supply, recycling, water conservation, and increased efficiency across all sectors are available but face implementation constraints.	25.2, 25.5.1, Box 25-2

	Increased frequency and intensity of flood damage to settlements and infrastructure in Australia and New Zealand, driven by increasing extreme rainfall although the amount of change remains uncertain (*high confidence*).			In many locations, continued reliance on increased protection alone would become progressively less feasible.	Table 25-1, 25.4.2, 25.10.3, Box 25-8
North America	Throughout North America, it is *very likely* that the 21st century will witness decreases in water quality, and increases in flooding and droughts under climate change, with these impacts exacerbated by other anthropogenic drivers. It will also witness decreases in water supplies for urban areas and irrigation in some areas of North America, with confounding effects of development.				26.3, 26.8
Central and South America	For regions already vulnerable in terms of water supply, such as the semi-arid zones in Chile-Argentina, North Eastern Brazil, and Central America and the tropical Andes, glacier retreat and a reduction in water availability due to expected precipitation reduction and increased evapotranspiration demands are expected, affecting water supply for large cities, small communities, hydropower generation, and the agriculture sector.			Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability.	27.3.1, 27.6.1

REGION	RISKS — TERRESTRIAL ECOSYSTEMS, DROUGHT, & WILDFIRE	Climate Driver(s)	Era & Adaptation Potential	Adaptation Issues/Prospects	Chap. Ref.
Africa	Many fragile terrestrial and aquatic ecosystems are implicitly or explicitly water dependent. Impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical socio-political and economic footprint (*high confidence*).				22.3.2, 22.3.3
Europe	Changes in habitats and species will result in local extinction (*high confidence*) and continental scale shifts (*low/medium confidence*). Increasing local loss of native species and extinction of species across most sub-regions of Europe by 2050 (medium emissions) with economic development and land-use change. Introduction and expansion of invasive species, especially those with high migration rates, from outside Europe will increase with climate change (*medium confidence*).				23.4.4, 23.6.4, 23.6.5, 23.10, Table 23.2
	Climate change will increase damage to forests from pests and diseases in all sub-regions (*high confidence*), from wildfires in Southern Europe (*high confidence*), and from storms (*low confidence*).				23.4.4
Asia	Terrestrial systems are under increasing pressure from both climatic and non-climatic drivers. The projected changes in climate will impact vegetation and increase permafrost degradation during the 21st century (*high confidence*). The largest changes are expected in cold northern and high-altitude areas, where boreal and subalpine trees will *likely* invade treeless arctic and alpine vegetation, and evergreen conifers will *likely* invade deciduous larch forest.				24.2.2, 24.4.2, 24.4.3, 24.9.3
Austral-asia	Loss of montane ecosystems and some endemic species in Australia, driven by rising temperatures, increased fire risk and drying trends (*high confidence*).			Fragmentation of landscapes, limited dispersal, and evolutionary capacity limit adaptation options.	25.6.1
	Increased damages to ecosystems and settlements, economic losses, and risks to human life from wildfires in most of southern Australia and many parts of New Zealand, driven by drying trends and rising temperatures (*high confidence*).			Building codes, design standards, local planning mechanisms, and public education can assist with adaptation and are being implemented in regions that have experienced major events.	25.2, 25.6.1, 25.7.1, Box 25-6
North America	A global increase of 2°C would have widespread adverse impacts on many ecosystems, *likely* reducing biodiversity and ecosystem services (*high confidence*).				26.4
Central and South America	Continued climate change together with land use change and fire activity could cause much of the Amazon forest to transform abruptly to more open, dry-adapted ecosystems, and in doing so, put a large stock of biodiversity at elevated risk and create a large new net greenhouse gas source to the atmosphere (*low confidence*).			Rigorously applied adaptation measures could lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*).	4.2.2, 4.2.4, 4.3.3, Box 4-3, Box 4-4

Polar Regions	Continued climate change could push the boreal-arctic system across a tipping point in this century and cause an abrupt transformation of the ecology and albedo of this region, as well as the release of greenhouse gases from thawing permafrost and burning forests (*low confidence*).			Adaption measures will be unable to prevent substantial change in the boreal-arctic system (*high confidence*).	4.2, 4.3.3, Box 4-3, Box 4-4
REGION	**RISKS — COASTAL & MARINE SYSTEMS**	**Climate Driver(s)**	**Era & Adaptation Potential**	**Adaptation Issues/Prospects**	**Chap. Ref.**
Africa	Impacts of climate change, mainly through sea level rise, combined with other extreme events (such as high tide levels and high storm swells) have the potential to threaten coastal zones, particularly coastal towns (*high confidence*).				22.3.2, 22.3.4, 22.3.7
Europe	Costs of adapting dwellings or upgrading coast defense will increase under all scenarios (*high confidence*).				23.3.2, 23.6.5, 23.7.3
Asia	In the Asian Arctic, rising sea levels will interact with projected changes in permafrost and the length of the ice-free season to cause increased rates of coastal erosion (*high agreement, medium evidence*).				24.4.3
Austral-asia	Significant change in community structure of coral reef systems in Australia, driven by increasing sea-surface temperatures and ocean acidification (*high confidence*).			The natural ability of reefs to adapt to projected changes is limited.	Box CC-CR, 25.6.2, 30.5
	Widespread damages to coastal infrastructure and low-lying ecosystems in Australia and New Zealand if sea level rise exceeds 1m (*high confidence*). Risks from sea level rise *very likely* continue to increase beyond 2100 even if temperatures are stabilized.			Managed retreat is a long-term adaptation strategy for human systems but options for some ecosystems are limited due to rapidity of change & lack of suitable space for inland migration.	WGI AR5 13; Box 25-1, 25.6, 25.4.2
Polar Regions	Shifts in the timing of seasonal biomass production could disrupt matched phenologies in food webs, leading to decreased abundance of high latitude marine organisms (*medium confidence*).				28.2.2, 28.3.2
REGION	**RISKS — HUMAN SYSTEMS**	**Climate Driver(s)**	**Era & Adaptation Potential**	**Adaptation Issues/Prospects**	**Chap. Ref.**
Africa	Spatial convergence of impacts in different sectors creates impact “hotspots” involving new interactions, for example, in Sub-Saharan Africa where global warming at the high end of the range projected for this century, i.e., more than 4°C above preindustrial levels, would be especially disruptive, resulting in high risk of reduced extent of croplands, reduced length of the growing season, increased hunger, and increased malaria transmission.				19.3.2
	Temperature rise and a reduction in growing season length by mid-century are expected to significantly reduce crop productivity with strong adverse effects on food security. New challenges to food security are emerging as a result of strong urbanization trends on the continent and increasingly globalized food chains, which require better understanding of the multi-stressor context of food and livelihood security.				22.3.4
Europe	Increasing heat wave mortality across most sub-regions of Europe by 2050 (medium emissions) with economic development and land-use change. Particularly in Southern Europe, increased frequency and intensity of heat waves (*high confidence*) will have adverse implications for health, agriculture, energy production, transport, tourism, labor productivity, and built environment (*medium confidence*).				23.2.2, 23.5.1, Tables 23-4, 23-5
	Climate warming will decrease space heating demand and increase cooling demand (*high confidence*), with income growth driving the largest part of this increase from 2000-2050 (especially in eastern regions) (*medium confidence*). Climate change will increase problems associated with overheating in domestic housing.			Energy efficient buildings and cooling systems as well as demand-side management will reduce future energy demands.	23.3.2, 23.3.4
	Climate change will increase yields in Northern Europe (*medium confidence*) but decrease cereal yields in Southern Europe (*high confidence*).				23.4.1, 23.4.2, 23.5.1

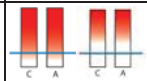
	Climate change will decrease hydropower production from reductions in rainfall in all sub-regions except Scandinavia (*high confidence*). Climate change will inhibit thermal power production during summer (*medium confidence*).			Plant modifications and operational changes can reduce adverse impacts.	23.3.4
	Increasing damage of cultural buildings and loss of cultural landscapes across most sub-regions by 2050 (medium emissions). Climate change and sea level rise will damage cultural heritage and iconic places such as Venice (*medium confidence*). Some cultural landscapes will be lost forever (*low/medium confidence*).				23.5.4, Table 23-5
Asia	Impacts of climate change on food production and security will vary by region with many regions experiencing productivity decline (*medium confidence*), e.g., in the case of rice production, with lower yields due to shorter growing periods and heat-induced sterility. Some regions are already near the critical temperature threshold. In parts of Asia, increases in flood and drought will exacerbate rural poverty due to negative impacts on rice crops and increases in food prices and costs of living (*high confidence*).			There are many potential adaptation strategies such as crop breeding, but research on their effectiveness is limited.	24.4.4, 24.4.6
	More frequent and intense heat-waves will increase mortality and morbidity in vulnerable groups. Increases in heavy rain and temperature will increase the risk of diarrheal diseases and malaria (*high confidence*).				24.4.6
Austral-asia	Increasing morbidity, mortality, and infrastructure damages during heat waves in Australia, resulting from increased frequency and magnitude of extreme temperatures (*high confidence*). Vulnerable populations include the elderly, children, and those with existing chronic diseases.			Aging trends and prevailing social dynamics constrain effectiveness of adaptation responses.	25.8.1
	Significant reduction in food production in the Murray-Darling Basin, far south-eastern Australia, and some eastern and northern areas of New Zealand if scenarios of severe drying are realized (*high confidence*).			More efficient water use, allocation, and trading would increase the resilience of systems in the near term but cannot prevent significant reductions in agricultural production and severe consequences for ecosystems and some rural communities at the dry end of the projected range.	25.2, 25.5.1, 25.7.2, Box 25-5
North America	Without adaptation, projected changes in temperature, precipitation, and extreme events would result in notable productivity declines in major crops by the end of the 21st century (*very high confidence*). Given that North America is a significant source of global food supplies, there will *likely* be a negative effect on global food security if projected productivity declines are not addressed with substantial investments in adaptation (*medium confidence*).			Adaptation may ameliorate many climate impacts to agriculture, but current institutional support mechanisms are insufficient to ensure effective, equitable, and sustainable adaptation strategies.	26.5
Central and South America	Climate-change-related changes in agricultural productivity are expected to vary greatly spatially. In Southeastern South America, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (SRES: A2, B2) (*medium confidence*). In Central America, northeast Brazil, and parts of the Andean region, increases in temperature and decreases in rainfall could decrease productivity in the short-term (before 2025), threatening food security of the poorest populations.				27.3.4
	It is *very likely* that climate variability and change may exacerbate current and future risks to health, given the region's vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, and pollution.				27.3.7
Polar Regions	Spatial convergence of impacts in different sectors creates impact "hotspots" involving new interactions, for example in the Arctic where sea ice loss and thawing disrupts transportation, buildings, other infrastructure, and potentially disrupts Inuit culture (*high confidence*).				19.3.2
	Significant impacts on the availability of key subsistence marine and terrestrial species are projected as climate continues to change with the ability to maintain economic livelihoods being affected (*high confidence*). Changing sea-ice conditions will result in more difficult access for hunting marine mammals.				28.2.6
Small Islands	Spatial convergence of impacts in different sectors creates impact "hotspots" involving new interactions, for example in the environs of Micronesia, Mariana Island, and Papua New Guinea where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification (*high confidence*).				19.3.2

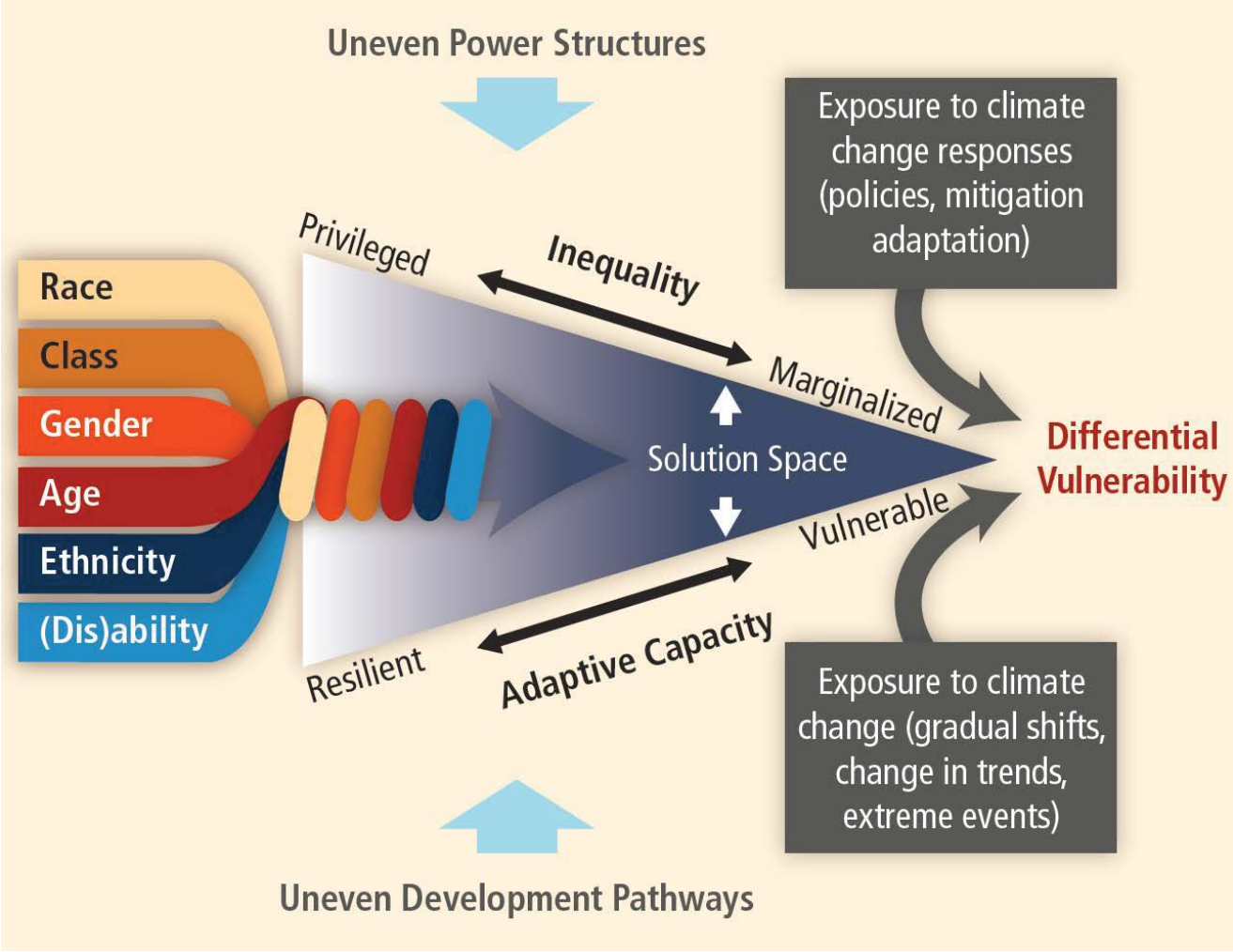
Table SPM.5: A selection of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in the report. The examples underscore the complexity of risks determined by various climatic hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, demographic changes, or tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climate-change-related harm and loss can occur. The examples illustrate that current global megatrends (e.g., climate change, urbanization, demographic changes), in combination and in specific development contexts (e.g., in low-lying coastal zones), can generate new systemic risks that go far beyond existing adaptation and risk management capacities, particularly in highly vulnerable regions. [Table 19-3]

Hazard/Stressor	Key vulnerabilities	Key risks	Emergent risks
Examples from terrestrial and inland water systems			
Rising air, soil, and water temperature.	Exceedence of eco-physiological climate tolerance limits of species, increased viability of alien organisms.	Loss of native biodiversity, increase in alien organism dominance.	Cascades of native species loss due to interdependencies.
	Epidemiological response to spread of temperature-sensitive vectors (insects).	Novel or much more severe pest and pathogen outbreaks.	Interactions between pest, drought, and fire interactions can lead to new risks and large negative impacts on ecosystems.
Examples from ocean systems			
Rising water temperature, increase of (thermal and haline) stratification, and marine acidification. [6.1.1] *(also Chapter 24)*	Tolerance limits of endemic species surpassed, increased abundance of invasive organisms, high vulnerability of warm water coral reefs and respective ecosystem services for coastal communities. [6.2.2, 6.2.5]	Loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms, loss of coral cover and associated ecosystems with reduction of biodiversity. [6.3.2]	Enhancement of risk due to interactions, e.g., acidification and warming for calcareous organisms. [6.3.5]
Examples from urban areas			
Inland flooding.	Urban areas with large numbers of poor, uninsured people exposed to flood events including low-income informal settlements. Environmental health consequences from overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure combined with widespread impermeable surfaces. Inadequate local governance. Increased mosquito and water borne diseases.	Increasing urban flooding with increasing volume and velocity of flood waters on the one hand and increasing vulnerability on the other leads to key risks particularly in urban areas with large numbers of people who are poor and/or exposed to flooding.	Larger and more frequent flooding impacting a much larger population. Impacts reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight; abandonment of urban districts and the creation of high risk/high poverty spatial traps.
Changing hazard profile including novel hazards and new multi-hazard complexes.	Newly exposed populations and infrastructure, especially for those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks.	Risks from failures within coupled systems, e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications, psychological shock from unanticipated risks.	Loss of faith in risk management institutions. Potential for large events that are magnified by a lack of preparation and capacity to respond.
Examples from human health			
Increasing frequency and intensity of extreme heat. *(also chapter 19)*	Older people living in cities are most vulnerable to heat waves, and their population is projected to triple from 2010-2050.	Increased mortality and morbidity during heat waves, particularly in people with pre-existing conditions.	Overloading of health and emergency services. Mortality, morbidity, and productivity loss, particularly for manual workers in hot climates.
Increasing temperatures, increased variability in precipitation.	Food insecurity translates into malnutrition, which is among the largest disease burdens in poorer populations.	Progress in reducing mortality and morbidity from malnutrition may slow or reverse and constitutes a new key risk.	Combined impacts of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequity, and on-going food insecurity for the poor.
Examples from livelihoods and poverty			
Soaring demand (and prices) of biofuels due to climate change policies.	Unclear and/or insecure land tenure arrangements.	Risk of dispossession of land due to "land grabbing" in developing countries.	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production.
Increasing frequency of extreme events (droughts, floods). For example if 1:20 year drought/flood becomes 1:5 year flood/drought.	Livelihoods subject to damage to their productive assets (e.g. in case of droughts – herds of livestock; if floods – dikes, fences, terraces).	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years.	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.

Hazard/Stressor	Key vulnerabilities	Key risks	Emergent risks
Examples from Chapter 19			
Warming and drying (degree of precipitation changes uncertain). [WGI AR5 SPM, TS.5.3, 11.3, 12.4]	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; socio-cultural constraints on some adaptation options. [19.2.2, 19.3.2, 19.6.1, 19.7.5]	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition, limited coping and adaptation options increase the risk of harm and loss. [19.3.2]	Negative outcomes to sending and/or receiving regions from migration of populations due to limits on agricultural productivity and livelihoods. [19.3.2, 19.4.2]
Examples from Africa			
Increasing temperature.	Health of exposed and vulnerable groups (increased exposure to heat, change in the transmission dynamics of vector-borne diseases).	Increase in disease burden – changes in the patterns of infection. Decrease in outdoor worker productivity due to high temperature, increase in heat related morbidity and mortality.	Emerging and re-emerging disease epidemics.
	Vulnerability of aquatic systems and vulnerability of aquatic ecosystem services due to increased water temperatures.	Loss of aquatic ecosystems and risks for people who might depend on these resources.	
Examples from Europe			
Extreme weather events. *(also Chapter 19)*	Limited coping and adaptive capacity as well as high sensitivity of different sectors, e.g., transport, energy, and health.	Stress on multiple sectors can cause systemic risks due to interdependencies among sectors.	Disproportionate intensification of risk due to increasing interdependencies.
Examples from Asia			
Thawing of permafrost due to rising temperature in northern Asia.	Existence of structures and infrastructure on permafrost and high dependence of civil life on them.	Instability of or damage to structures and infrastructures.	Projected exacerbation of instability of residential buildings, pavements, pipelines used to transport petroleum and gas, pump stations, and extraction facilities.
Projected increase in frequency of various extreme events (heat waves, floods, and droughts) and sea level rise. *(also Chapter 19)*	Convergence of livelihoods and properties into coastal megacities, especially into areas not sufficiently protected against natural hazards.	Loss of human life and assets due to coastal floods accompanied by increasing vulnerabilities caused by occurrence of other extreme events like heat waves and droughts.	Projected increase in disruption of basic services such as water supply, sanitation, energy provision, and transportation systems, which themselves could increase vulnerabilities.
Examples from Australasia			
Warming and increased temperature high extremes in Australia. [25.2, Table 25-1, Figure 25-5]	Urbanization, aging of population and vital infrastructure. [25.3, Box 25-9, 25.10.2]	Increase in morbidity, mortality, and infrastructure failure during heat waves. [25.8.1, 25.10.2]	Increasing risk from compound extreme events across time, space and governance scales, and cumulative adaptation needs. [25.10.2, 25.10.3, Box 25-9]
Potential for sea level rise beyond 2100 exceeding 1m [25.2, WGI AR5 Chapter 13]	Long lifetime of coastal infrastructure, concentration and further expansion of coastal population and assets; conflicting priorities and time preferences constraining adaptation options; limited scope for managed retreat in highly developed areas.	Widespread damages to coastal infrastructure and low-lying ecosystems. [Box 25-1, 25.10.2]	
Examples from North America			
Increases in frequency and/or intensity of extreme events, such as hurricanes, river and coastal floods, heat waves, and droughts. [26.2] *(also Chapter 19)*	Declining state of physical infrastructure in urban areas as well as increases in income disparities. [26.7]	Risk of serious harm and losses in urban areas, particularly in coastal environments due to enhanced vulnerabilities of social groups and physical systems combined with increases of extreme weather events. [26.8]	Inability to reduce vulnerability in many areas results in increase in risk greater than change in physical hazard. [26.8]
Higher temperatures, decreases in runoff, and lower soil moisture. [26.2, 26.3]	Increasing vulnerability of small landholders in agriculture. [26.5]	Increased losses and decreases in agricultural production increase food and job insecurity for small landholders and social groups in that region. [26.5]	Increasing risks of social instability and local economic disruption due to internal migration. [26.2, 26.8]

Table SPM.6: Examples of potential tradeoffs among adaptation objectives. [Table 16-2]

Sector	Strategy	Adaptation Objective	Real or Perceived Externality
Agriculture	Biotechnology and genetically modified crops	Enhance drought and pest resistance; enhance yields	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments
	Subsidized drought assistance; crop insurance	Provide financial safety net for farmers to ensure continuation of farming enterprises	Creates moral hazard and inequality if not appropriately administered
	Increased use of chemical fertilizer and pesticides	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased discharge of nutrients and chemical pollution to the environment; increased emissions of greenhouse gases; increased human exposure to pollutants
Biodiversity	Migration corridors; expansion of conservation areas	Enable natural adaptation and migration to changing climatic conditions	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges
	Anticipatory endangerment listings	Enhance regulatory protections for species potentially at-risk due to climate change	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to economic development
	Assisted migration	Facilitate conservation of valued species	Potential for externalities for ecological and human systems due to species relocation
Coasts	Sea walls	Protect assets from inundation and/or erosion	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands
	Managed retreat	Allow natural coastal and ecological processes; reduce long-term risk to property and assets	Undermines private property rights; significant governance challenges associated with implementation
	Migration out of low-lying areas	Preserve public health and safety; minimize property damage and risk of stranded assets	Loss of sense of place and cultural identity; erosion of kinship and familial ties; impacts to receiving communities
Water resources management	Desalination	Increase water resource reliability and drought resilience	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation
	Water trading	Maximize efficiency of water management and use; increases flexibility	Undermines public good/social aspects of water
	Water recycling/reuse	Enhance efficiency of available water resources	Perceived risk to public health and safety



Box SPM.3 Figure 1: Intersecting, simultaneous, and dynamic axes of privilege and marginalization, shaped by people's multiple identities and embedded in uneven power relations and development pathways. Together, they result in differential vulnerability to the same exposure to climate change and climate responses. [Figure 13-4]

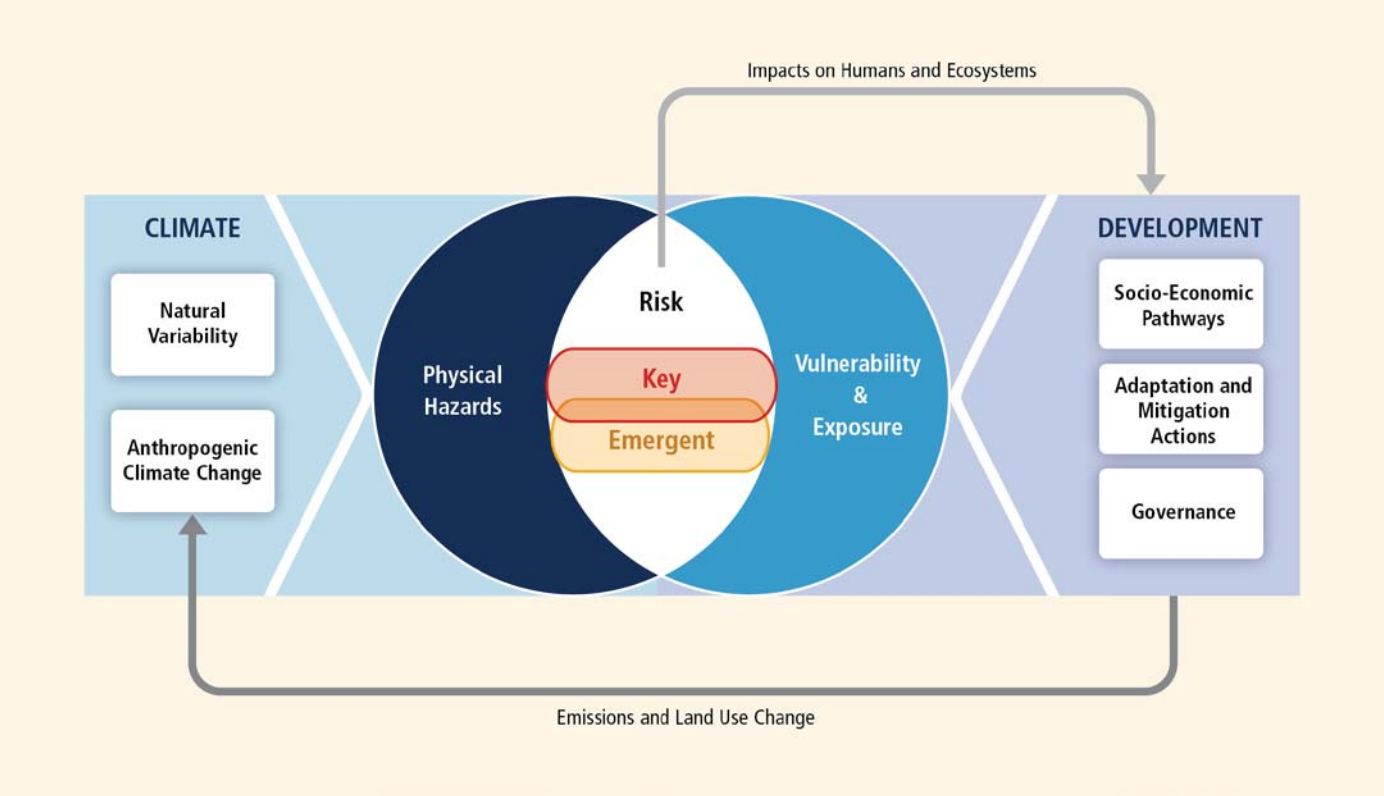


Figure SPM.1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions. Changes in both the climate system (left) and development processes (right) are key drivers of the different core components (vulnerability, exposure, and physical hazards) that constitute risk. The definition and use of “key” and “emergent” are indicated in Section C.ii. [19.1, Figure 19-1]

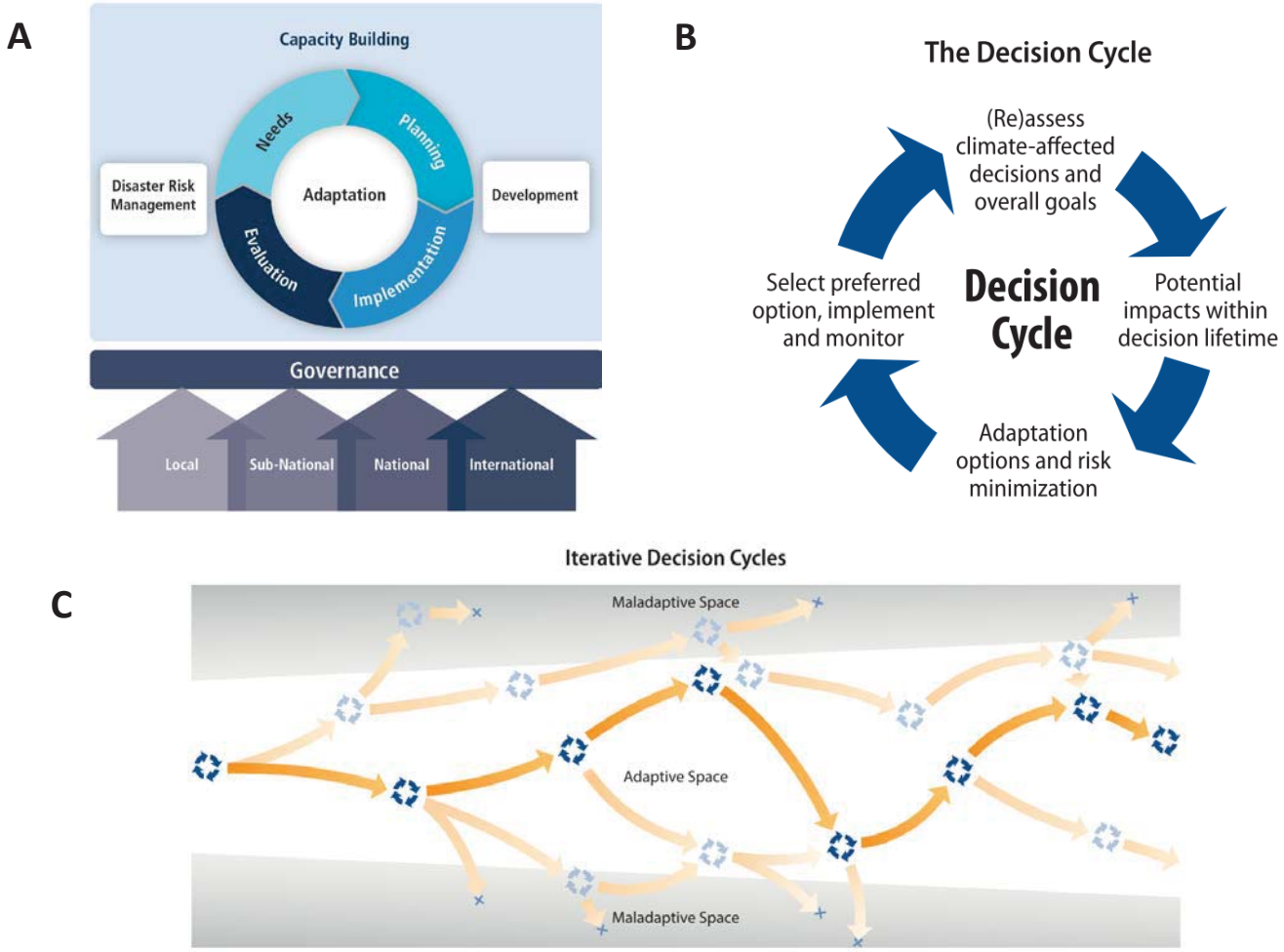
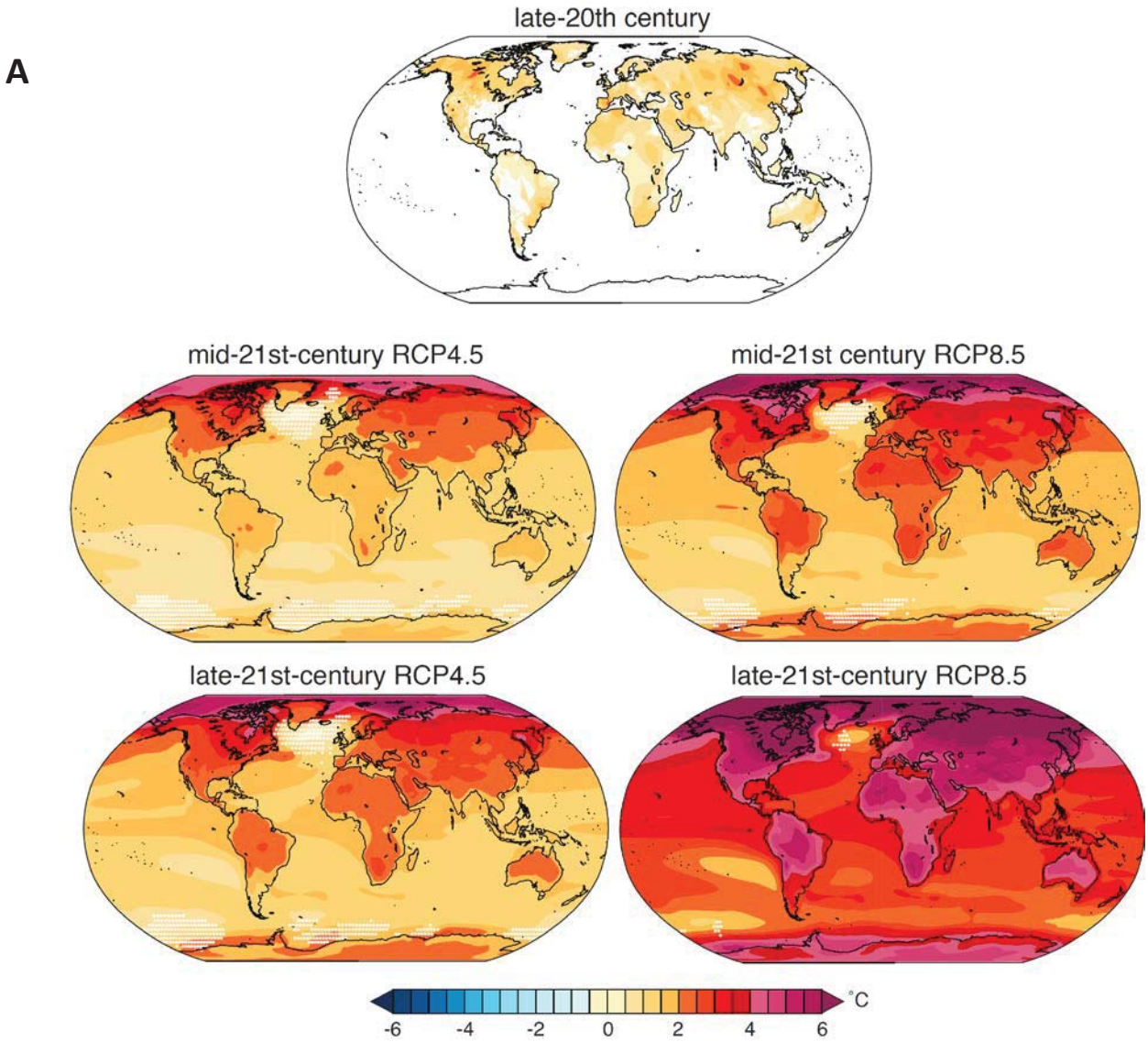
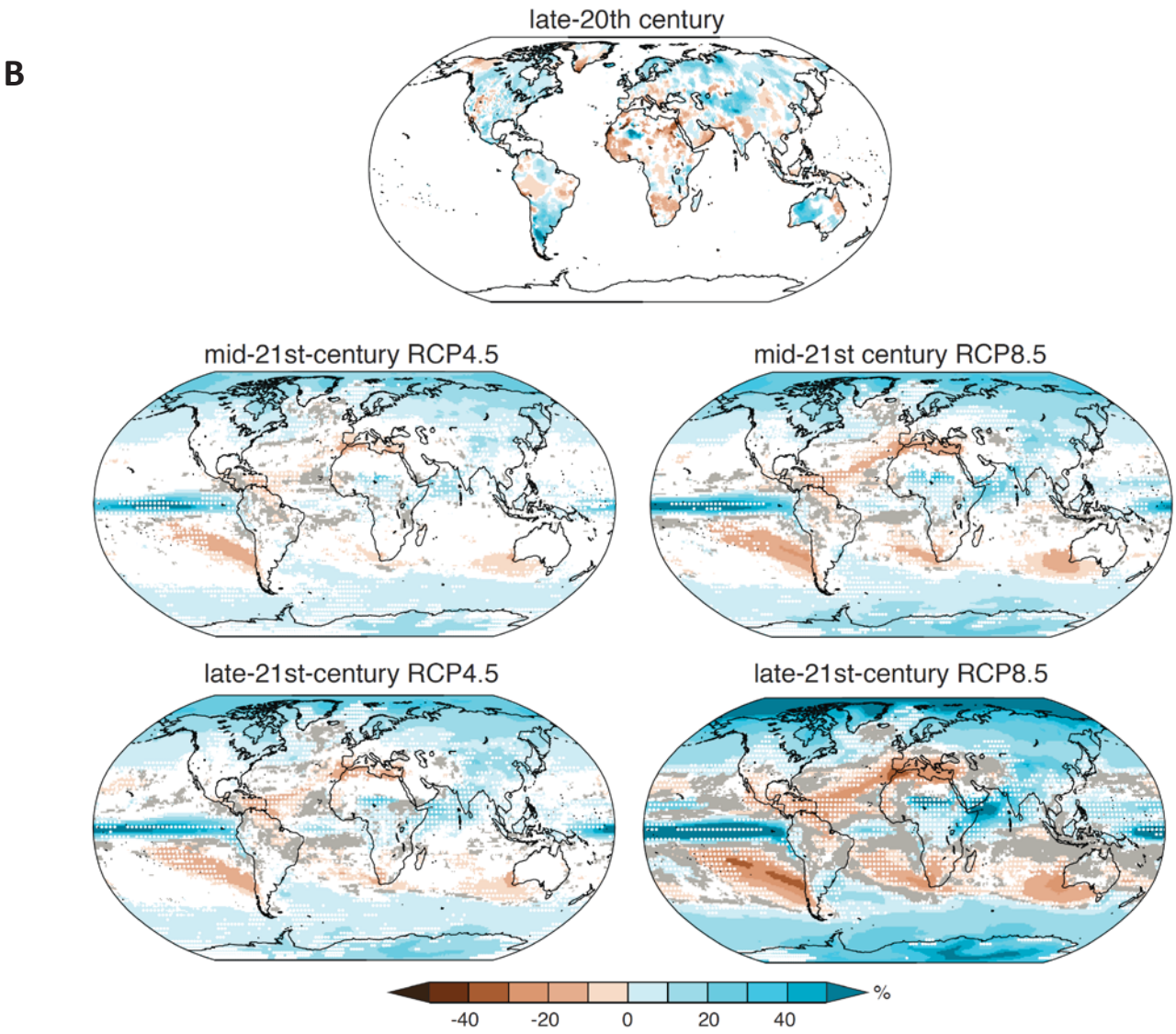


Figure SPM.2: Illustration of iterative response to climate change. (A) Four main phases of planned adaptation as a cyclic, iterative process: needs, planning, implementation, and evaluation. Efforts in adaptation can be linked with development or disaster risk management. Adaptation governance at multiple scales underlies capacity. (B) In the context of iterative risk management, each individual adaptation decision cycle comprises well known aspects of risk assessment and management. (C) A sequence of adaptation decisions creates an adaptation pathway. Some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but there is no single correct adaptation pathway and judgment of outcomes depends strongly on societal values, expectations, and goals. [Figures 15-1, 16-2, 25-6]



Box SUM.4 Figure 1: Changes in annual average temperature (A) and precipitation (B). For observations (top map, A and B; CRU), differences are shown over land between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For projections (bottom four maps, A and B; CMIP5), four classes of results are displayed. (1) White indicates areas where for >66% of models the annual average change is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions, more than 2/3 of models show no significant change in the annual average using this measure of significance, although this does not imply no significant change at seasonal or shorter time-scales such as months to days. (2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions, more than 2/3 of models show a significant change in annual average, but less than 2/3 agree on whether it will increase or decrease. (3) Colors with white circles indicate the change averaged over all models where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on whether the annual average will increase or decrease. In these regions, more than 2/3 of models show a significant change in annual average and more than 2/3 (but less than 90%) agree on whether it will increase or decrease. (4) Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether the annual average will increase or decrease. For models that have provided multiple realizations for the climate of the recent past and the future, results from each realization were first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios were calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065. See also Annex I of WGI AR5. [Box CC-RC]



Box SUM.4 Figure 1: Changes in annual average temperature (A) and precipitation (B). For observations (top map, A and B; CRU), differences are shown over land between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For projections (bottom four maps, A and B; CMIP5), four classes of results are displayed. (1) White indicates areas where for >66% of models the annual average change is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions, more than 2/3 of models show no significant change in the annual average using this measure of significance, although this does not imply no significant change at seasonal or shorter time-scales such as months to days. (2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions, more than 2/3 of models show a significant change in annual average, but less than 2/3 agree on whether it will increase or decrease. (3) Colors with white circles indicate the change averaged over all models where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on whether the annual average will increase or decrease. In these regions, more than 2/3 of models show a significant change in annual average and more than 2/3 (but less than 90%) agree on whether it will increase or decrease. (4) Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether the annual average will increase or decrease. For models that have provided multiple realizations for the climate of the recent past and the future, results from each realization were first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios were calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065. See also Annex I of WGI AR5. [Box CC-RC]

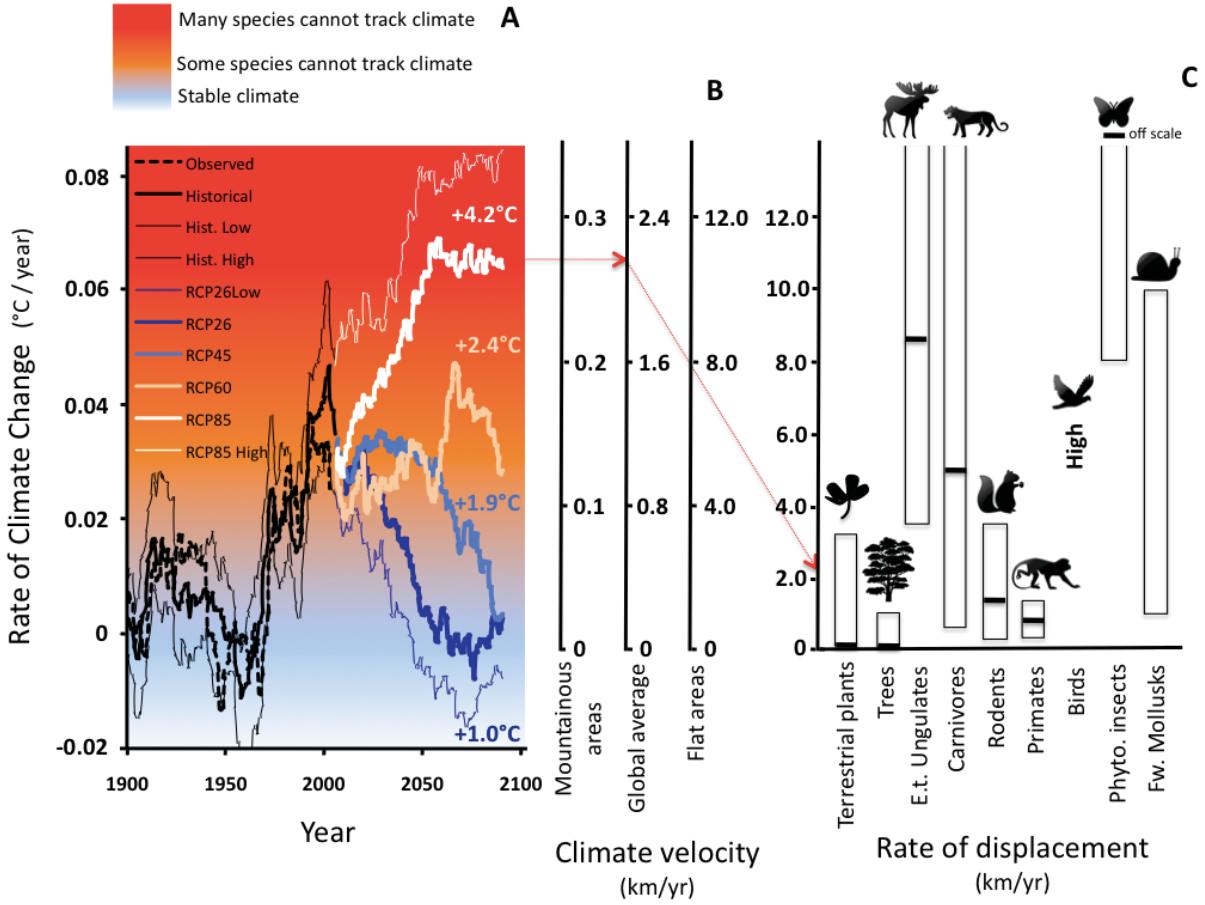


Figure SPM.3: Synthetic overview of projected abilities of some terrestrial and freshwater species to track climate by movement across landscapes. (A) Rates of climate change for global land areas. Black dotted line shows observed rates of climate change. Other rates were calculated from the CMIP5 ensemble for the historical period (black heavy line, with upper and lower bounds as light black lines) and for the future based on the four RCPs. A lower bound is given for RCP 2.6, and an upper bound for RCP 8.5. (B) Corresponding climate velocities, providing indication of the speed at which species' ranges would need to move to track changing climatic conditions. In mountainous areas with low climate velocities, species would only need to move short distances upslope to track a warming climate. In flat areas with high climate velocities, such as the Amazon basin, species would need to move large distances to track a warming climate. (C) Maximum estimated rates of displacement of several terrestrial and freshwater species groups, indicating how fast these groups can move across landscapes. Rates of species displacement are well defined for plants, especially trees, but less well defined for other groups. Displacement rates do not generally account for biotic interactions or human intervention that may speed or hinder dispersal. The thin red arrows give an example of interpretation: a rate of climate change of 0.065 °C/yr (approximately equal to projected rates by mid-century for RCP 8.5) corresponds to ~2.2 km/yr global average climate velocity. This global-average velocity would exceed projected maximum capacity for displacement for most plants, most primates, many rodents, and some less mobile species of other groups. For RCP 2.6, most species would be able to track climate by mid-century. Color gradient in panel A provides overall representation of the ability of species to track climate change. Detailed spatial analyses and maps of species displacement can be found in the references cited in WGII Chapter 4. E.t ungulates = even-toed ungulates; Phyto. insects = phytophagous (herbivorous) insects; Fw. mollusks = freshwater mollusks. [Figure 4-6]

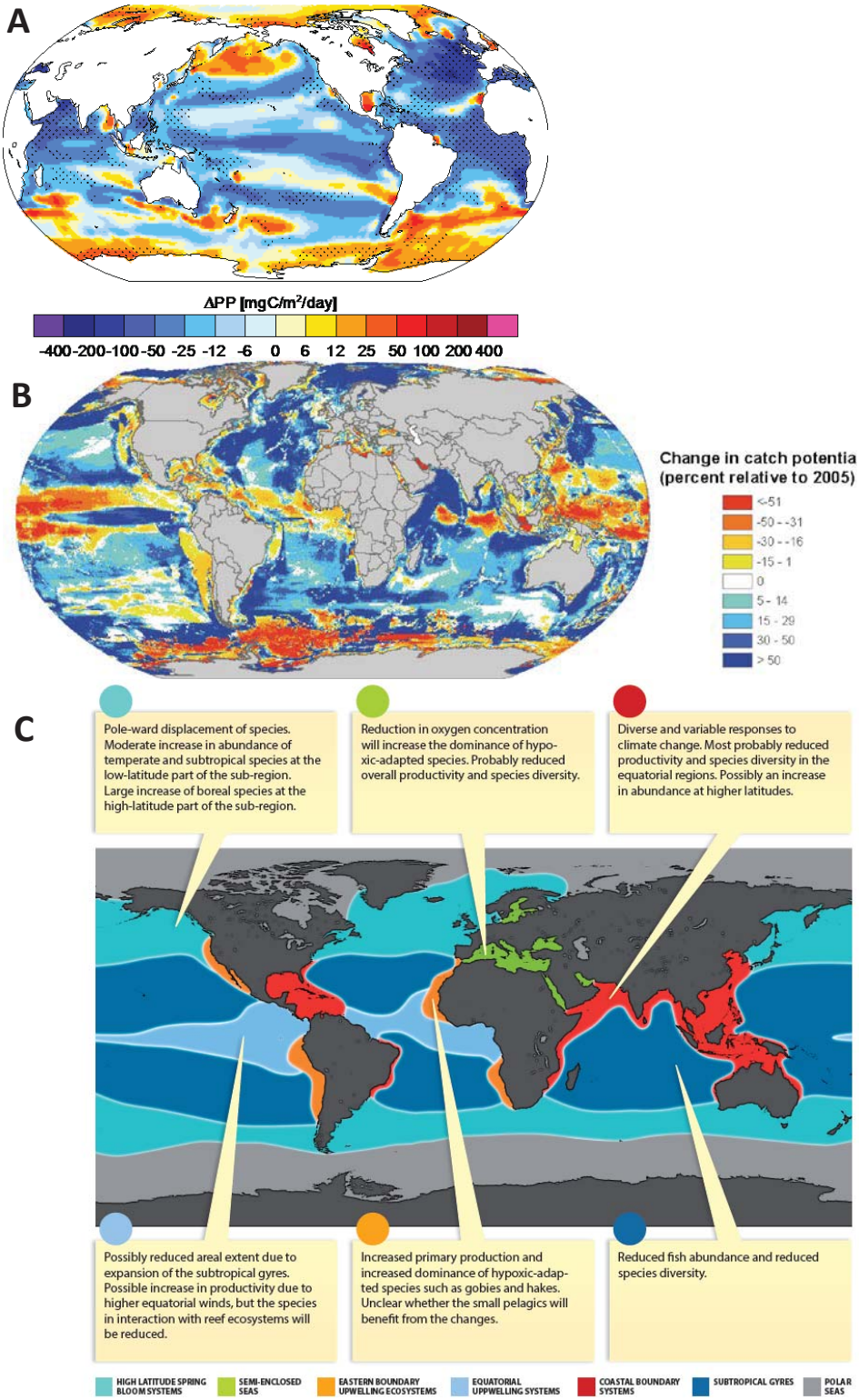


Figure SPM.4: (A) Multi-model mean changes of projected net primary production. To indicate consistency in the sign of change, regions are stippled where all models (four in total) agree on the sign of change. Changes are annual means under SRES A2 for the period 2080 to 2099 relative to 1870 to 1889. (B) A projection of maximum fisheries catch potential of 1000 species of exploited fishes and invertebrates from 2000 to 2050 under SRES A1B. (C) Example of changes occurring within fisheries across the ocean. [Figures 6-14, 6-15, and 30-15]

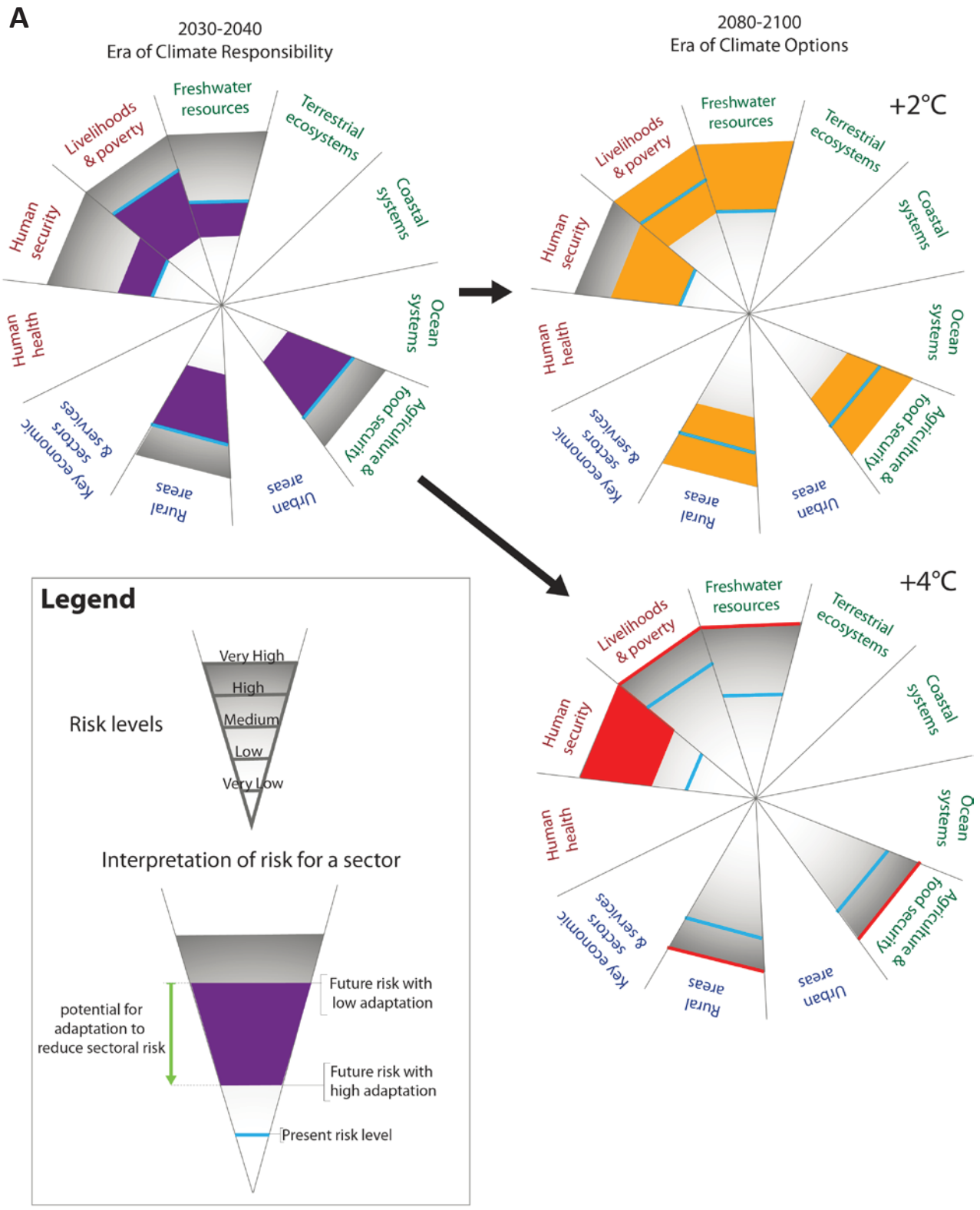


Figure SPM.5: Estimated risk from climate change to selected sectors and systems in Africa (A), Europe (B), and North America (C), for different time frames (2030-2040 and 2080-2100), under two levels of global average warming above preindustrial (2°C and 4°C) and different assumptions about adaptation to manage these risks. Levels of risk and of adaptation are differentiated by colored shading, ranging from high adaptation to low adaptation. Estimated risks rely on expert judgments. The risk categories reflect the overall structure of Part A of the WGII AR5. [Figures 22-7 and 26-6]

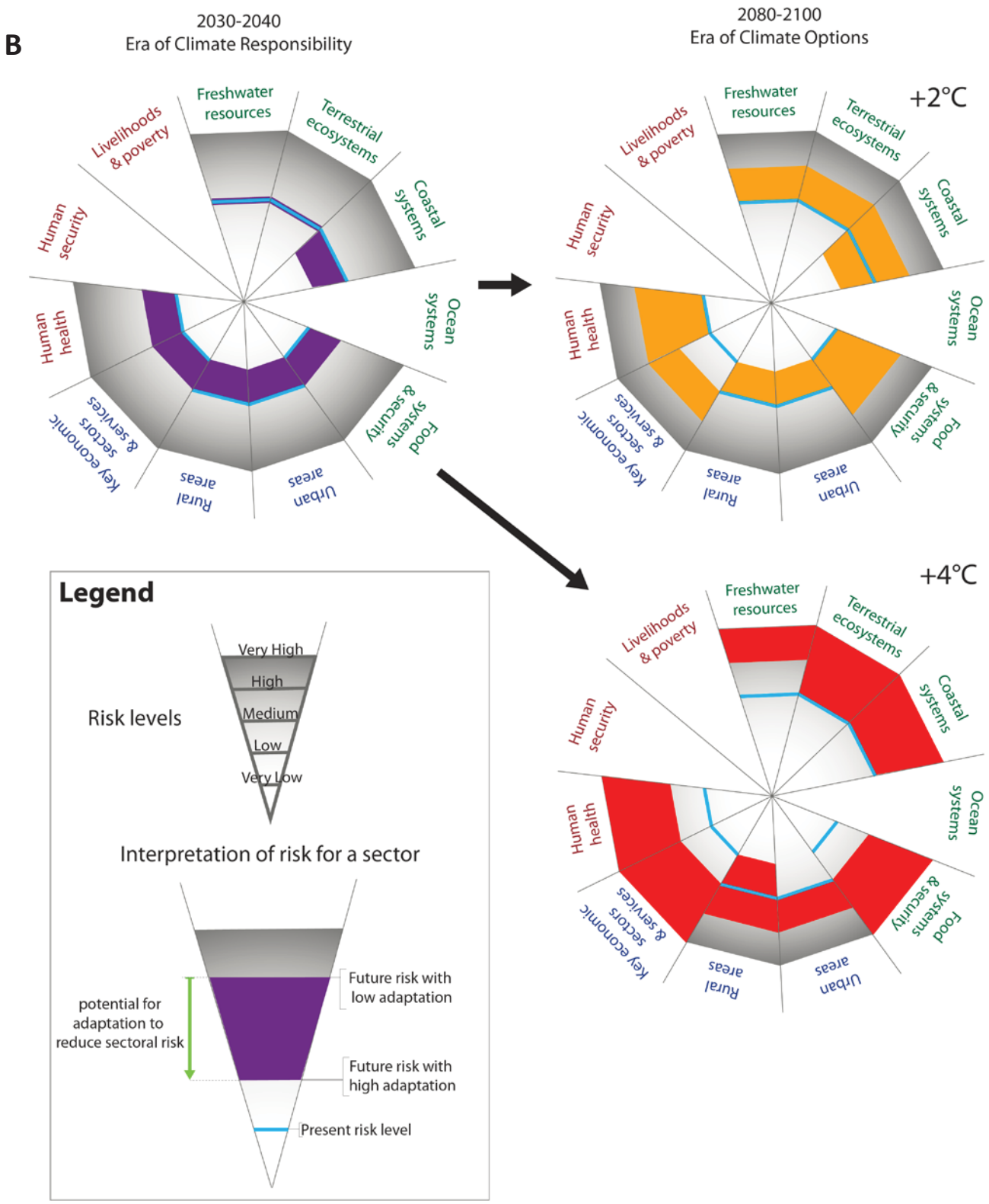
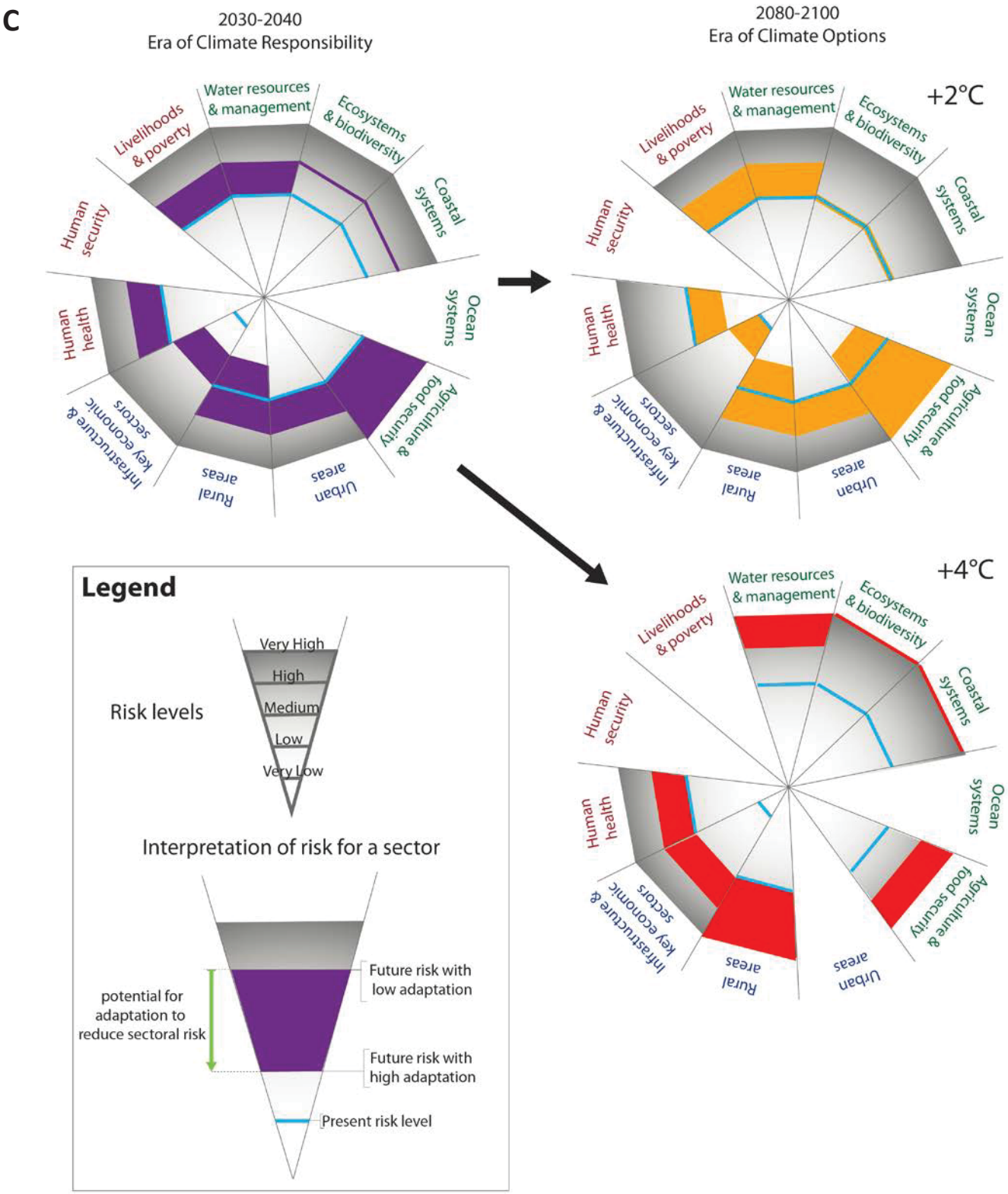


Figure SPM.5: Estimated risk from climate change to selected sectors and systems in Africa (A), Europe (B), and North America (C), for different time frames (2030-2040 and 2080-2100), under two levels of global average warming above preindustrial (2°C and 4°C) and different assumptions about adaptation to manage these risks. Levels of risk and of adaptation are differentiated by colored shading, ranging from high adaptation to low adaptation. Estimated risks rely on expert judgments. The risk categories reflect the overall structure of Part A of the WGII AR5. [Figures 22-7 and 26-6]



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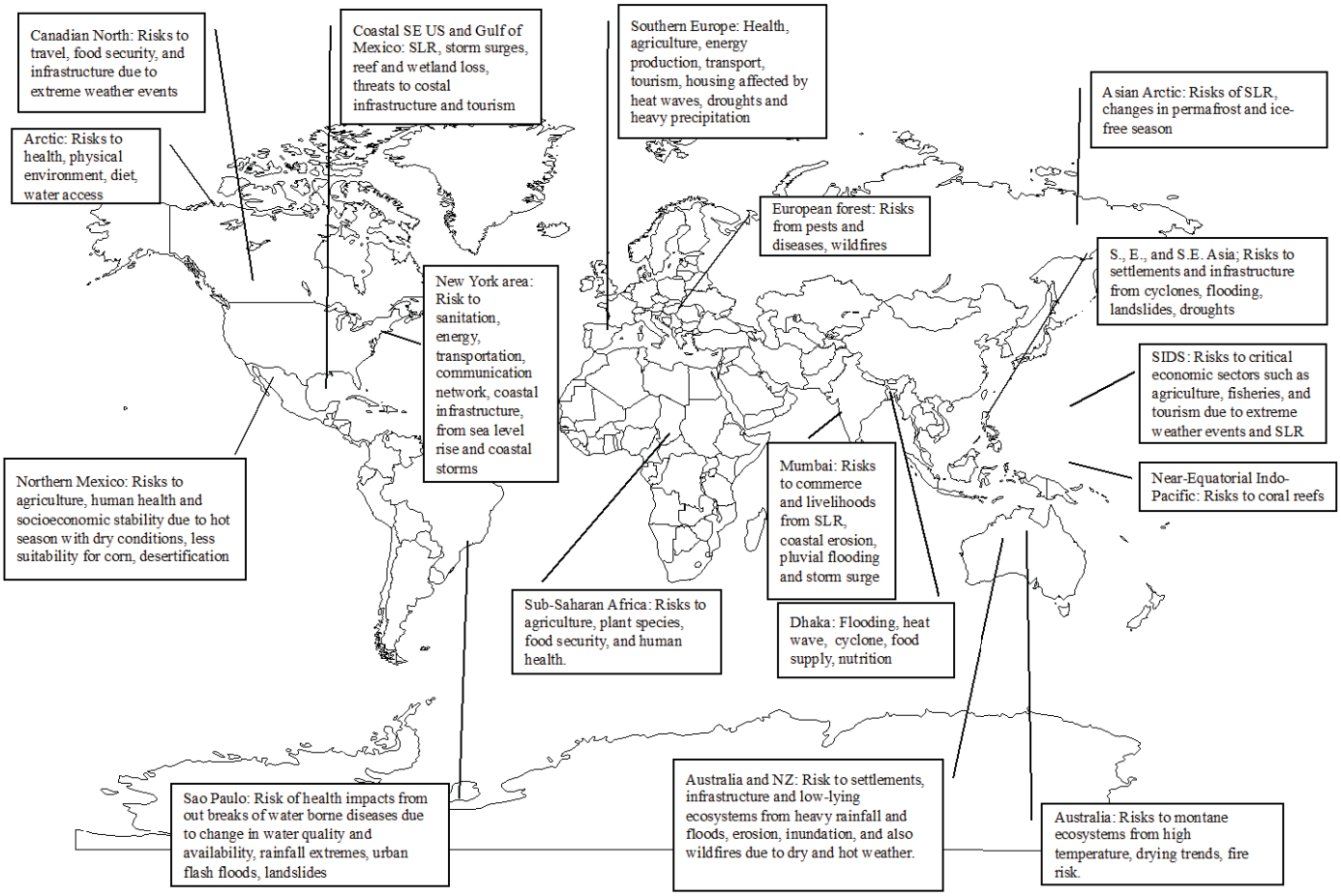
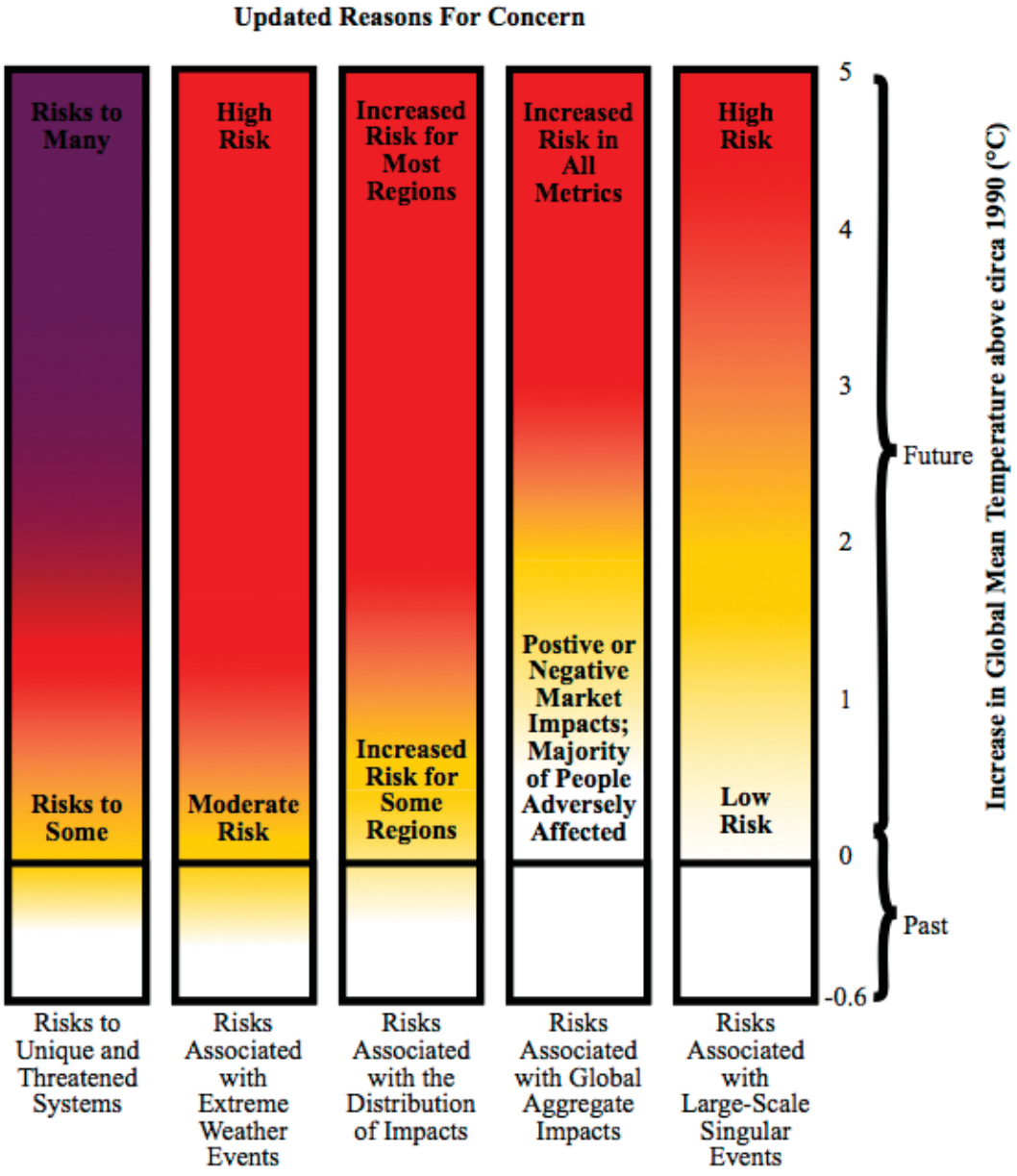
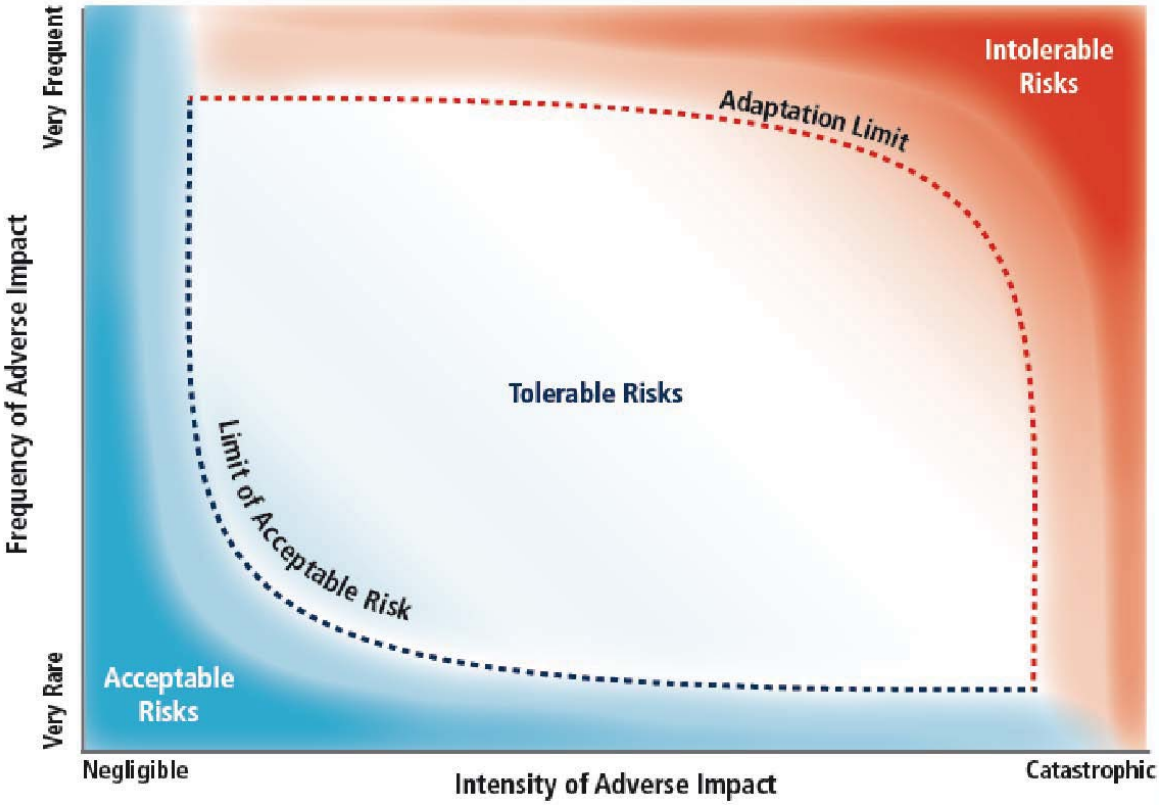


Figure SPM.6: Some salient examples of multi-impacts hotspots identified in this assessment. [Figure 19-2]



Box SPM.6 Figure 1: The dependence of risk associated with reasons for concern (RFCs) about climate change, updated based on expert judgment in this assessment. The color scheme indicates the additional risk due to climate change (with white to purple indicating the lowest to highest level of risk, respectively). Purple color, introduced here for the first time, reflects the assessment that unique human and natural systems tend to have very limited adaptive capacity. [Figure 19-5]



Box SPM.7 Figure 1: Conceptual model of acceptable, tolerable, and intolerable risks and implications for limits to adaptation. [16.2, Figure 16-1]

Climate Change 2014: Impacts, Adaptation, and Vulnerability
TECHNICAL SUMMARY

Coordinating Lead Authors
Christopher Field (USA), Vicente Barros (Argentina), Katharine Mach (USA), Michael Mastrandrea (USA)

Lead Authors
Maarten van Aalst (Netherlands), Neil Adger (UK), Paulina Aldunce (Chile), Douglas Arent (USA), Jonathon Barnett (Australia), Richard Betts (UK), Eren Bilir (USA), Joern Birkmann (Germany), JoAnn Carmin (USA), Dave Chadee (Trinidad and Tobago), Andrew Challinor (UK), Monalisa Chatterjee (USA/India), Wolfgang Cramer (Germany), Yuka Estrada (USA/Japan), Jean-Pierre Gattuso (France), Yasuaki Hijioka (Japan), Ove Hoegh-Guldberg (Australia), He-Qing Huang (China), Gregory Insarov (Russian Federation), Roger Jones (Australia), Sari Kovats (UK), Patricia Romero Lankao (Mexico), Joan Nymand Larsen (Iceland), Iñigo Losada (Spain), Jose Marengo (Brazil), Roger McLean (Australia), Linda Mearns (USA), Reinhard Mechler (Austria), John Morton (UK), Isabelle Niang (Senegal), Taikan Oki (Japan), Jane Mukarugwiza Olwoch (South Africa), Maggie Opondo (Kenya), Elvira Poloczanska (Australia), Hans-O. Pörtner (Germany), Margaret Hiza Redsteer (USA), Andy Reisinger (New Zealand), Aromar Revi (India), Daniela Schmidt (UK), Rebecca Shaw (USA), William Solecki (USA), John Stone (Canada), Ken Strzepek (UNU/USA), Avelino Suarez (Cuba), Petra Tschakert (USA), Riccardo Valentini (Italy), Sebastian Vicuna (Chile), Alicia Villamizar (Venezuela), Katharine Vincent (South Africa), Rachel Warren (UK), Thomas Wilbanks (USA), Poh Poh Wong (Singapore), Gary Yohe (USA)

Review Editors
Paulina Aldunce (Chile), Jean Ometto (Brazil), Nirivololona Raholijao (Madagascar), Kazuya Yasuhara (Japan)

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INTRODUCTION

Climate change is shifting patterns of risks and opportunities in a complex and changing world. The Working Group II contribution to the IPCC's Fifth Assessment Report (AR5) acknowledges the complexity of climate change and of the world in which it is unfolding. It recognizes that impacts of climate change will vary across regions and populations, through space and time, dependent on myriad factors including the extent of mitigation and adaptation. It provides information on patterns of changing risks and on how they can be managed.

For the past two decades, Working Group II has developed assessments of climate change impacts, adaptation, and vulnerability. The Working Group II contribution to the IPCC's AR5 builds from the Fourth Assessment Report (AR4), published in 2007, and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), published in 2012 (Box TS.1). Section A of this summary characterizes observed impacts, vulnerabilities, and responses to date. Section B, building from exposure, vulnerability, and physical hazards as determinants of risk, considers approaches for managing the risks of climate change. Section C examines the range of future risks across sectors and regions, highlighting where choices matter for reducing risks through mitigation and adaptation. Section D explores the broader interactions among mitigation, adaptation, and sustainable development.

Box TS.2 defines concepts central to the Working Group II contribution to the AR5. To accurately convey the degree of certainty in key findings, the report relies on the consistent use of calibrated uncertainty language, introduced in Box TS.3. Chapter sections in square brackets indicate the assessment supporting findings in this summary.

_____ START BOX TS.1 HERE _____

Box TS.1. The Context of the Assessment

The literature available for assessing climate change impacts, adaptation, and vulnerability has more than doubled since 2005 (*very high confidence*). The diversity of the topics and regions covered by the literature has similarly expanded, as well as the geographic distribution of the authors contributing to the knowledge base for climate change assessments (Box TS.1 Figure 1). Production of climate change literature has increased in the developing countries, although their institutions lag those in developed countries regarding access to and production of climate change literature. The unequal distribution of literature, which is influenced by factors such as scientific funding and capacity building, presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. [1.1.1, Fig. 1-1]

[INSERT BOX TS.1 FIGURE 1 HERE
Box TS.1 Figure 1: Results of English literature search using the Scopus bibliographic database from Reed Elsevier Publishers. (a) Annual global output of publications on climate change and related topics: impacts, adaptation, and costs (1970-2010). (b) Country affiliation of authors of climate change publications summed for IPCC regions for three time periods: 1981-1990, 1991-2000, and 2001-2010, with total number during the period 2001-2010. (c) Results of literature searches for climate change publications with individual countries mentioned in publication title, abstract, or key words, summed for all countries by geographic region. [Figure 1-1]]

The evolution of the IPCC assessments of impacts, adaptation, and vulnerability indicates an increasing emphasis on humans, their role in managing resources and natural systems, and the societal impacts of climate change (*very high confidence*). The expanded focus on societal impacts and responses is evident in the composition of the IPCC author teams, the literature assessed, and the content of the IPCC assessment reports. Three important characteristics in the evolution of the Working Group 2 assessment reports are an increasing attention to: (i) Adaptation limits and transformation in societal and natural systems; (ii) Synergies between multiple variables and factors that affect sustainable development, including risk management; and (iii) Institutional, social, cultural, and value-related issues. [1.1, 1.2]

Adaptation has emerged as a central area of work in climate change research, in country level planning, and in the implementation of climate change strategies (*high confidence*). The body of literature shows an increased

focus on capitalizing upon adaptation opportunities and on the interrelations among adaptation, mitigation, and alternative sustainable pathways. In spite of the uncertainty of future impacts and adaptation, the literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. [1.1.4]

The treatment and communication of uncertainties in IPCC reports have evolved over time, reflecting iterative learning and more coherent guidance across all Working Groups (*high confidence*). An integral feature of IPCC reports is communicating the strength and uncertainties in the scientific understanding underlying assessment findings. In Working Group II, the use of calibrated language began in the Second Assessment Report, where most chapters used qualitative levels of confidence for their Executive Summary findings. Based on experience, guidance notes were developed for subsequent assessment reports. The AR5 Guidance Note continues to emphasize a theme from all three guidance documents to date: the importance of clearly linking each key finding and corresponding assignment of calibrated uncertainty language to associated chapter text, as part of the traceable account of the author team's evaluation of evidence and agreement supporting that finding (see Box TS.3). [1.1.2.2, Box 1-1]

_____ END BOX TS.1 HERE _____

_____ START BOX TS.2 HERE _____

Box TS.2. Terms Critical for Understanding the Summary

Core concepts defined in the glossary and used throughout the report include:

Climate change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulation of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. In contrast, the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities that alter the atmospheric composition, and climate variability attributable to natural causes.

Exposure: The presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected.

Impacts: Effects on natural and human systems. In this report, the term 'impacts' is used to refer to the effects on natural and human systems of physical events, of disasters, and of climate change.

Risk: The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk is often represented as probability of occurrence of a hazardous event(s) multiplied by the consequences if the event(s) occurs. This report assesses climate-related risks.

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, which seeks to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate.

Incremental adaptation – Adaptation actions where the central aim is to maintain the essence and integrity of an incumbent system or process at a given scale.

Transformational adaptation – Adaptation that changes the fundamental attributes of a system in response to actual or expected climate and its effects.

Resilience: The ability of a social, ecological, or socio-ecological system and its components to anticipate, reduce, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner.

Transformation: A change in the fundamental attributes of a system, often based on altered paradigms, goals, or values. Transformations can occur in technological or biological systems, financial structures, and regulatory, legislative, or administrative regimes.

_____ END BOX TS.2 HERE _____

_____ START BOX TS.3 HERE _____

Box TS.3. Communication of the Degree of Certainty in Assessment Findings

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, the Working Group II contribution to the Fifth Assessment Report relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment).

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The summary terms to describe available evidence are: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, author teams additionally evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Box TS.3 Figure 1 illustrates the flexible relationship between the summary terms for evidence and agreement and the confidence metric. For a given evidence and agreement statement, different confidence levels could be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

[INSERT BOX TS.3 FIGURE 1 HERE
Box TS.3 Figure 1: Evidence and agreement statements and their relationship to confidence. The shading increasing towards the top right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence. [Figure 1-4]]

When author teams evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, a finding can include likelihood terms (see below) or a more precise presentation of probability. Use of likelihood is not an alternative to use of confidence: an author team will have a level of confidence about the validity of a probabilistic finding. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence.

Term*	**Likelihood of the outcome**
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms used in limited circumstances are *extremely likely:* 95– 100% probability; *more likely than not:* >50–100% probability; and *extremely unlikely:* 0–5% probability.

_____ END BOX TS.3 HERE _____

A) VULNERABILITIES, IMPACTS, AND ADAPTATION IN A COMPLEX AND CHANGING WORLD

This section presents observed effects of climate change, including detection and attribution of impacts on human and natural systems. It evaluates sensitivities to climate, factors determining vulnerability and exposure, and the role of non-climate stressors. It considers that the effects of climate variability, climate extremes, and climate change are determined through the interaction of vulnerability and exposure with physical hazards. The section also examines coping and adaptation responses to climate events and conditions to date. It identifies challenges and options based on adaptation experience, and it looks at what has motivated previous adaptation actions in the context of climate change and broader objectives.

A.i. Vulnerabilities and Observed Impacts across Sectors with Regional Examples

Impacts of recent observed climate change on physical, biological, and human systems have been detected on all continents and in most oceans (*high confidence*). This conclusion is strengthened by observations since the AR4 as well as through more extensive analyses of earlier observations. Most reported impacts of climate change are attributed to regional warming of the atmosphere and the ocean, with lower confidence in attribution of observed impacts to shifts in rainfall patterns. There is emerging evidence of impacts of ocean acidification. For many natural systems, new or stronger evidence for substantial and wide-ranging impacts of climate change exists, including the cryosphere, water resources, coastal systems, and ecosystems on land and in the ocean. For managed ecosystems and human systems, the effects of changing social and economic factors often dominate over any direct impact of climate change. Despite this, numerous impacts of climate change have been detected. See Table TS.1 for examples of observed impacts across regions. [18.3-18.6]

[INSERT TABLE TS.1 HERE
Table TS.1: Observed impacts attributed to climate change with *medium* (*) or *high* (**) confidence. Impacts for physical, biological, and human systems are characterized across eight major world regions. For each observed impact, confidence in detection is equal to or greater than confidence in attribution. [Table 18-6, 18-7, 18-8, 18-9]]

Confidence in attribution is assigned through assessment of the relative contribution to a system's behavior by all known drivers affecting the system's dynamics, using scientific methods and also involving an assessment of confidence in detection. Formal meta-analysis or aggregated assessments of many observations or studies can help to improve confidence. In most studies, the attribution of observed impacts and vulnerabilities is related to all changes in climate that represent deviations from historical means and/or historic variability. Only a smaller number of robust attribution studies link responses in physical and biological systems to *anthropogenic* climate change. Though evidence is improving, there is a persistent gap of knowledge regarding how large parts of the world are being affected by observed climate change. Research to improve the timeliness and knowledge about the detection and attribution is needed in particular for the risk of extreme events. [18.1, 18.2.1, Box 18-1, 18.7]

Factors determining vulnerability and exposure

Climatic and biophysical drivers interact with systemic non-climatic drivers of vulnerability and exposure to shape differential risks and impacts (*very high confidence*). Since AR4 the framing of adaptation has moved further from a focus on biophysical vulnerability to the wider social and economic drivers of vulnerability. Factors affecting vulnerability and exposure involve a complex mix of physical and socio-economic factors, including gender, age, health, social status and ethnicity, environmental degradation, technology gaps, conflict, and institutions, political systems, and governance structures. Uneven socio-economic development pathways at the national and global level create and perpetuate systemic vulnerabilities. This unevenness results from structural conditions of poverty, inequality, and marginalization, as well as differential levels of health and human security. See Box TS.4. [13.1, 14.1, 14.2, 19.6.1]

Vulnerability and exposure of communities or social-ecological systems to climatic hazards are dynamic and thus varying across temporal and spatial scales. Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socio-economic development pathways and the vulnerability and exposure of people. Changes in poverty or socio-economic status, race and ethnicity compositions, age structures, and

governance have had a significant influence on the outcome of past crises associated with climatic hazards. [15.2.4, 19.6.1]

Understanding of future vulnerability of human and social-ecological systems to climate change remains limited due to incomplete consideration of socio-economic dimensions (*very high confidence*). Future vulnerability will depend on factors such as wealth and its distribution across society, patterns of aging, access to technology and information, labor force participation, societal values, and mechanisms and institutions to resolve conflicts (see also Box TS.4). These dimensions have received only limited attention and are rarely included in vulnerability assessments, and frameworks to integrate social and cultural dimensions of vulnerability with biophysical impacts and economic losses are lacking. [25.3, 25.4, 25.11]

Impacts from recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts include the alteration of ecosystems, altered food production, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. These experiences are consistent with a significant adaptation deficit in developing and developed countries for some sectors and within some regions. See Table TS.2.

- Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011); the Victorian heat wave (2009) increased heat-related morbidity and caused 374 excess deaths, and intense bushfires destroyed over 2,000 buildings and led to 173 deaths; widespread drought in south-east Australia (1997-2009) and many parts of New Zealand (2007-2009) resulted in economic losses (approximately A$7.4b in south-east Australia in 2002-03 and NZ$3.6b in direct and off-farm output in 2007-09) and mental health problems in some areas of Australia. [13.2.1, Table 25-1, 25.8.1, Box 25-5, Box 25-6, Box 25-8]
- The observed impacts of extreme weather events indicate the current vulnerability of Europe across multiple sectors. [Table 23-3]
- In North America, most economic sectors have been affected by and responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). Heat extremes currently result in increases in mortality and morbidity, with impacts that vary by age and socioeconomic factors (*very high confidence*). Coastal storm events periodically cause excess mortality and morbidity via a range of direct and indirect pathways in North America, particularly along the east coast of the US, and the gulf coast of both Mexico and the US (*high confidence*). Many infrastructural elements across North America are currently vulnerable to extreme weather events (*medium confidence*). Infrastructures, particularly in water resources and transportation, are in many cases deteriorating, and are thus more vulnerable to extremes than strengthened ones. Extreme events have caused significant damage to infrastructure in many parts of North America. [26.6, 26.7]
- Research to improve the timeliness and knowledge about detection and attribution is needed in particular for the risk of extreme events. [18.7]

[INSERT TABLE TS.2 HERE
Table TS.2: Illustrative selection of some recent extreme impact events for which the role of climate has been assessed in the literature. The table shows confidence assessments as to whether the associated meteorological events made a substantial contribution to the impact event, as well as confidence assessments of a contribution of anthropogenic emissions to the meteorological event. The assessment of confidence in the findings is not necessarily a conclusion of the listed literature but rather results from assessment of the literature. Assessment of the role of anthropogenic emissions in the impact event requires a multi-step evaluation. [Table 18-4]]

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Box TS.4. Multidimensional Vulnerability to Climate Change

People who are socially, economically, culturally, politically, or institutionally marginalized are typically most at risk from adverse impacts of climate change and climate change responses. However, such heightened vulnerability does not occur in isolation; rather, it is observed along intersecting and simultaneous axes of marginalization and privilege, including not only income and assets but also gender, class, race, ethnicity, age, and (dis)ability (Box TS.4

Figure 1). Other dimensions include resource access, location, legal systems, and voice. Understanding differential adaptive capacity for individuals, households, and communities requires attention to multidimensional inequality, deprivation, and power, as well as context-specific constellations in which certain dimensions drive differential vulnerability while others play a secondary role or are absent (e.g., class and gender in one case versus race, gender, and age in another case). Few studies depict the full spectrum of these differences and the ways in which they interact to shape resilience or vulnerability, and thus attribution remains a challenge. Since inequality is not just a consequence of climate change, but also a key cause and amplifier of its impacts, inequality-sensitive analyses are needed for effective and efficient adaptation.

[INSERT BOX TS.4 FIGURE 1 HERE

Box TS.4 Figure 1: Intersecting yet simultaneous and dynamic axes of privilege and marginalization, shaped by people's multiple identities and embedded in uneven power relations and development pathways. Together, they result in differential vulnerability to the same exposure to climate change and climate change responses. These intersecting dimensions ("intersectionality") illustrate systemic vulnerability and multidimensional deprivation that determine inequality and adaptive capacity while being transformed as a result of negative climate change impacts and risks as well as consequences of policy responses, often to the detriment of the poor and disadvantaged. [Figure 13-4]]

Example impacts and risks of climate change and climate change responses:

- Differential impacts on men and women arise from distinct roles in society, the way these roles are enhanced or constrained by other dimensions of privilege and marginalization, and the nature of response to hazards. [9.3.5, 13.2.1]
- Both male and female deaths are recorded after flooding, dependent on socio-economic disadvantage and culturally-imposed expectations to save lives. While women are generally more sensitive to heat stress, more male workers are reported to have died largely due to gender roles and responsibilities related to outdoor and indoor work [11.4.1, 13.2.1]
- Women often experience additional duties as laborers and caregivers as a result of weather events, climate, and extreme events, as well as responses (e.g., male outmigration), while facing more psychological and emotional distress, loss in food intake, and in some cases increasing incidences of domestic violence. [9.3.5, 9.4.1, 13.2.1]
- Privileged members of society can benefit from climate change impacts and response strategies, due to their flexibility in mobilizing and accessing resources and positions of power, often to the detriment of others. [13.2.1]
- Populations that presently experience high levels of ill-health are more seriously affected than those currently in relatively good health. [11.3]
- Children and the elderly are often at higher risk, due to narrow mobility, susceptibility to infectious diseases, reduced caloric intake, and social isolation. While adults and older children are more severely affected by some climate-sensitive vector borne diseases such as dengue, young children are more likely to die from or be severely compromised by diarrheal diseases. [11.5, 13.2.1]
- In most urban areas, low-income groups face larger climate change risks and impacts because of poor quality and insecure housing, inadequate infrastructure and lack of provision for health care, emergency services, and measures for disaster risk reduction. [8.1.4]
- Indigenous peoples' livelihoods and lifestyles, often dependent on natural resources, are highly sensitive to climate change and climate change policies, especially those that marginalize their knowledge and perspectives. [12.3]
- Pastoralists and artisanal fisher folk may be becoming more vulnerable to climate change, partly due to neglect, misunderstanding, or inappropriate policy toward them on the part of governments. [9.3.5]
- The ability of migrants to adapt to climate change may be declining in destination areas, particularly in urban centers in developing countries. One primary mechanism is the clustering of low income migrants in flood-prone and landslide-prone high density housing. [12.4.2]
- In areas where violent conflict has destabilized society and damaged natural and social capital people are particularly vulnerable to climate change. [12.5]
- One-dimensional narratives, particularly of women and other marginalized groups, deny agency and portray people's vulnerability as their intrinsic problem. [13.2.1]
- Disadvantaged groups without access to land and labor, including female-headed households, are disproportionately harmed by climate change response mechanisms (e.g., CDM, REDD+, large-scale land acquisition for biofuels, and planned agricultural adaptation projects). [9.3.5, 12.2, 12.5, 13.3.1]

_____ END BOX TS.4 HERE _____

Freshwater resources

Glaciers worldwide continue to shrink (*very high confidence*). New glacier lakes have formed, and existing ones have changed. Seasonal ice in many lakes and rivers forms later and breaks up earlier. A major part of these changes can be attributed to climate change (*high confidence*). [3.2.3, 18.3.1.3, 18.5, Figure 18-3]

Widespread changes and degradation of permafrost of both high-latitude and high-elevation mountain regions have been observed over the past years and decades *(high confidence).* The permafrost boundary has been moving polewards and to higher elevations, and the active layer thickness has increased at many sites (*medium confidence* in attribution to climate change). [18.3.1, 18.5]

Hydrological systems have changed in many regions due to changing rainfall or melting glaciers, affecting water resources, water quality, and sediment transport (*medium confidence*). In many river systems, the frequency of floods has been altered by climate change (*low* to *medium confidence*). The duration of droughts in some regions has been altered by climate change (*medium confidence*). In the last decades, warming has caused a shift towards earlier maximum spring discharge, decreased spring snowpack, and sometimes decreased magnitudes of snowmelt floods in regions with seasonal snow storage (*high confidence*, based on *high agreement, robust evidence*). Where more winter precipitation falls as rain than snow, winter low flows have increased significantly. Where the stream flow is lowest in summer, decreased snow storage has exacerbated summer low flows. [3.2.3, 18.3.1, 18.5]

Specific regional examples include the following. See also Table TS.1.

- In Asia, the Altai-Sayan, Pamir, and Tien Shan glaciers have lost on average 10% of their area and 15% of their ice volume since 1960. Rates of further glacier degradation depend mainly on increases in summer air temperature and changes in precipitation. [24.9.3]
- In North America, changes in climate trends include reductions in spring snowpack along with an earlier peak runoff over many areas (*very high confidence*). Attribution of observed changes to anthropogenic climate change has been established for some physical systems (e.g., snowpack). In most areas, impacts of climate variability such as floods, decreased water availability, and increased salinity of coastal water supplies, which are exacerbated by other anthropogenic drivers, are observed (*high confidence*). Water supply deficits are conducive to adaptive response, with many hard and soft approaches to adaptation currently available. [26.2, 26.3]
- In Central and South America, there have been changes in geophysical variables (cryosphere and runoff) that affect streamflow and ultimately water availability (*high confidence*). Since AR4, there is growing evidence that glaciers (both tropical and extratropical) are retreating and the cryosphere in the Andes is changing according to the warming trends. These changes affect streamflow availability in different seasons of the year. Robust trends are apparent, associated with changes in precipitation such as increasing runoff in the Southeastern South America region (La Plata basin), and decreasing runoff in the Central Andes (Chile, Argentina) and Central America. In contrast to these findings, no robust trend in streamflow in the Amazon Basin has been detected. [27.3.1]
- In the Arctic, the decline of summer sea-ice is occurring at a rate that exceeds most model projections (*high confidence*). In some regions of Antarctica, evidence of similarly rapid rates of change is emerging, particularly for ice shelves. There is some evidence, for example in the reduction of sea-ice extent in the Arctic and in the west Antarctic Peninsula, that the changes are non-linear and may be accelerating. [WGI AR5 Chapter 14]

Terrestrial and inland water systems

The magnitude of future climate change could approach that of many of the largest climatic changes observed in Earth history (*high confidence*). The planet's biota, carbon cycle, and associated feedbacks and services have responded to climate change in Earth history even when the rates of past global climate change were

slower than implied by higher warming scenarios (e.g., RCP 8.5). However, the impacts of climate change on terrestrial and freshwater ecosystems must also be considered in the context of non-climatic influences, both naturally-occurring and directly driven by humans. [4.2.2]

Plant and animal species have moved their ranges, altered their abundance, and shifted their seasonal activities in response to climate change in the past, and they are doing so now in many regions (*high confidence*). The broad patterns of species and biome movement towards the poles and higher in altitude in response to a warming climate are well established for the distant (*very high confidence*) and recent past (*medium confidence*). Seasonal activity of species has responded to warming over the last several decades based on extensive ground and satellite-based measurements (*high confidence*). Species have already started to migrate out of protected areas and towards mountaintops over the last several decades due to a warming climate. Observations and models of the seasonal activities of species indicate that climate warming disrupts species life cycles and interactions between species, as well as altering ecosystem function. At local scales, observed and modeled species responses sometimes differ from qualitative predictions based on global scale indices of warming; this can often be explained by large variation in local scale climate response to global warming, changes in climate factors other than average temperature, non-climatic determinants of species distributions, interactions between climate and other simultaneous global change factors such as nitrogen deposition, and species interactions. No past climate changes are a precise analog to the current and projected climatic changes, so species responses inferred from the past only give indications, especially at the local scale. [4.2.2, 4.3.2, 4.3.3, 4.4.1, 18.3.2, 18.5]

There is *very low confidence* that observed species extinctions can be attributed to recent climate warming given the very low fraction of species for which global extinction has been ascribed to climate change and the tenuous nature of most attributions. However, in the specific case of Central American amphibians, there is *medium confidence* that recent warming has played a role in their extinctions. [4.3.2, 18.3.2, 18.5]

Increases in the frequency or intensity of ecosystem disturbances due to fires, pest outbreaks, wind-storms, and droughts have been detected in many parts of the world (*medium confidence*). Such changes beyond the range of historical natural variability will alter the structure, composition, and functioning of ecosystems (*high confidence*). These changes will often be manifested as relatively abrupt and spatially-patchy transitions following disturbances, rather than gradual and spatially-uniform shifts in location or abundance (*medium confidence*). There is evidence of an increase in tree mortality in many regions over the last decade, but there is *low confidence* in the detection of a global trend in increased mortality or in the attribution of such a global trend to climate change. In some regions, increased tree mortality is sufficiently intense and widespread as to result in forest dieback, which constitutes a major risk because of its large impacts on biodiversity, wood production, water quality, amenity, economic activity, and the climate itself. In detailed regional studies, particularly in western and boreal North America, observed tree mortality is detectable and can be attributed to the direct effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming (*high confidence*). [4.2.4, 4.3.2, 4.3.3, 4.3.4, Box 4-2, Box 4-3, Box 4-4, Figure 4-12]

Several major terrestrial ecosystems are undergoing broad-scale changes that can be characterized as early warnings for coming regime shifts, in part due to climate change. Climate change is a driver of widespread shrub encroachment in the Arctic tundra (*high confidence*) and of boreal forest tree mortality (*low confidence*). Observed recession and degradation of the Amazon forest cannot be attributed to climate change. [18.3.2, 18.5.6, 18.5.7]

Specific regional examples include the following. See also Table TS.1.

- In Europe, climate change has already affected the distribution and abundance of some animals and plant species in Europe (*high confidence*). Observed climate change is affecting a wide range of flora and fauna in Europe, including plant pests and diseases and the vectors of animal diseases (*medium confidence*). Observed climate warming has increased forest productivity in northern Europe (*medium confidence*) and fire incidence in southern Europe (*high confidence*). [23.4.1, 23.4.3, 23.4.4, Table 23-4, Table 23.6, 23.6.4]
- In North America, climate change is already affecting many ecosystems (*high confidence*). Forests are being affected by fire, drought, pests, and other climate-related stresses. [26.4]
- In Central and South America, land cover change is a key driver of environmental change with significant impacts that may increase potential negative impacts from climate change. Deforestation and land degradation are mainly attributed to increased extensive and intensive agriculture, both from traditional

export activities such as beef and soy production, but more recently from biomass for biofuel production. Agricultural expansion has affected fragile ecosystems such as the edges of the Amazon forest and the tropical Andes, increasing the vulnerability of communities to extreme climate events, particularly floods, landslides, and droughts. Even though deforestation rates in the Amazon have decreased substantially in the last eight years to a current value of 0.29%, the lowest for all forest biomes in Brazil, other regions like the Cerrado and the Chaco forests still present high levels of deforestation with rates as high as 1.33%. [27.2.2]

- In Central and South America, conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss, and in parallel is a driver of anthropogenic climate change. Plant species are rapidly declining in Central and South America; the highest percentage of rapidly declining amphibian species occurs also in Central and South America, with Brazil being among the countries with the most threatened species of birds, mammals, and freshwater fishes. However, the region has still large extensions of natural vegetation cover for which the Amazon is the main example. [27.3.2]
- **Climate change is impacting terrestrial and freshwater ecosystems in some areas of the Arctic and Antarctica.** This is due to ecological effects resulting from reductions in the duration and extent of ice cover and enhanced permafrost thaw (*very high confidence*) and through changes in the precipitation-evaporation balance (*medium confidence*). [28.2] The abundance and biomass of deciduous shrubs and grasses has increased substantially over large – but not all – parts of the Arctic tundra in recent years (*very high confidence*). It is *very likely* that most of this increase in biomass can be attributed to longer growing seasons and higher summer temperatures. The tree line has moved northwards and upwards in many, but not all, Arctic areas, and significant increases in tall shrubs have been observed in many places (*high confidence*). Other factors such as changes in herbivore grazing, anthropogenic disturbances, and changes in precipitation and the snow/water regime also influence the tree line and structural vegetation changes in the northern boreal forest. [28.2]

Coastal systems and low-lying areas

On-going warming and acidification of coastal waters have direct and indirect impacts on natural ecosystems (*very high confidence*). More than 70% of the world's coastlines have significantly warmed during the past 30 years. The increase in the acidity of seawater is much greater in some coastal areas than in the open ocean due to the combined effects of atmospheric CO_2 uptake and eutrophication. Both changes have wide-ranging consequences on coastal organisms and ecosystems, such as species survival and shifts, coral bleaching, and decreased rates of calcification. Reducing regional stressors represents an opportunity to strengthen the ecological resilience of these ecosystems, which may help them survive projected changes in ocean temperature and chemistry. See also Box TS.9. [5.3.4, 6.1.1, 6.2.2, 6.3.2, 6.5.2, 30.4, 30.5, Box CC-CR, CC-OA]

Due to the increased frequency of stress events arising from elevated sea temperatures, coral reefs have experienced increased mass bleaching and mortality (*very high confidence*). These events have contributed to the loss of reef building corals in many parts of the world since the early 1980s. [18.3.3, 18.3.4, Box 18-3, 18.5, Table 18-8, Box CC-CR]

Despite the known sensitivity of coastal systems to sea-level rise, local perturbations from regional variability in the ocean and human activities preclude the confident detection of sea level-related impacts attributable to climate change outside of the Arctic. [18.3.3]

Specific regional examples include the following. See also Table TS.1.

- In North America, coastal zones are being affected by multiple and often interacting climate stresses including higher temperatures, ocean acidification, coral reef bleaching, sea level rise, storm surges, and storms (*high confidence*). [26.4]
- In north-eastern Australia (since the late 1970s) and more recently in western Australia, high sea surface temperatures have repeatedly bleached coral reefs. [25.6.2]
- In Central and South America, coastal and marine ecosystems have been undergoing significant transformations that pose threats to fish stocks, corals, mangroves, places for recreation and tourism, and controls of pests and pathogens. Frequent coral bleaching events have been recently reported for the Mesoamerican Coral Reef. Some of the main drivers of mangrove loss are deforestation and land

conversion, agriculture, and shrimp ponds to an extent that the mangroves of the Atlantic and Pacific coasts of Central America are some of the most endangered on the planet. [27.3.3.1]

- Arctic sea ice has been shrinking in extent, thickness, and composition, with observed impacts on marine biology and the livelihoods of indigenous people (*medium* to *high confidence*). [18.3.1, 18.3.4, 18.4.7, 18.5.7]

Marine systems

Climate change is manifesting itself in the alteration of abiotic and biotic properties of the ocean (*high confidence*). The physical and chemical properties of the ocean have changed significantly over the past 60 years due to anthropogenic climate change, including properties such as circulation intensity, temperature, oxygen (O_2) and nutrient inventories, carbon dioxide, ocean pH, salinity, and light regime. Changes to ocean conditions have resulted in fundamental and extensive changes to organisms and ecosystems in the ocean. [6.1.1, 6.2.2, 6.3.2, 6.5.2, 18.3.3, 18.3.4, 30.4, 30.5, Box CC-CR, CC-OA]

Marine ecosystems have been and are being exposed to and affected by climate changes of different rates, magnitude, and duration (*very high confidence*). In Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts (*high confidence*). The fossil record and present field and laboratory observations confirm key environmental drivers and responses of ocean ecosystems to climate change including migration, altered ecosystem composition, changes in abundance, and extinctions. [6.1.2, 6.3]

Understanding of physiology combined with field observations demonstrates that vulnerability of most organisms is defined by their specialization on specific, limited temperature ranges and accordingly by their thermal sensitivity (*high confidence*). See Figure TS.1. Temperature defines the geographical distribution of species and their responses to climate change (*medium confidence*). Temperature extremes act through losses in abundance and habitat (e.g., sea ice and coastal), local extinction, and latitudinal shifts (*very high confidence*). Vulnerability is greatest in polar animals and in species living close to their upper thermal limits, for example in the tropics (*medium confidence*). [6.2.2, 6.2.3, 6.2.4, 6.2.5. 6.3.2, 6.5.2]

Warming is causing shifts in the geographical distribution, abundance, and migration patterns of species, paralleled by a reduction in their body size and a shift in the timing of seasonal activities. This results in altered interactions between species including changes in competition and predator-prey dynamics (*high confidence*). Increased temperatures have significantly altered the phenology or timing of key life-history events such as plankton blooms, migratory patterns, and spawning in fish and invertebrates over recent decades (*medium confidence*). There are many observations of poleward shifts in the distribution and abundance of fishes and invertebrates and/or of their shifts to deeper and cooler waters. Poleward shifts of plankton have occurred up to 250 km per decade, up to 30 times faster than terrestrial species. See Figure TS.1. [6.2.2, 6.2.5, 6.3, 6.5, 30.4, 30.5]

The combination and often amplification of climate change drivers acting globally and additional human-induced local drivers, such as overfishing, pollution, and eutrophication exacerbating hypoxia, result in enhanced vulnerability of natural and human systems to climate related forcings presently and into the future (*high confidence*). Observations include the progressive redistribution of species, changes in species' abundance, and the reduction in marine biodiversity in sensitive regions and habitats, putting the sustained provision of ecosystem services and fisheries productivity at risk. Socio-economic vulnerability is high particularly in tropical developing countries, progressively increasing the risk of reduced food supply, income, and employment. Key uncertainties include the upscaling of climate change effects from organism to ecosystem level, the adaptive capacity of marine organisms and human societies to these impacts, the interactions with other human drivers, the sustenance of biogeochemical functions and productivity in the global ocean, and the effectiveness of climate mitigation and adaptation measures. [6.3.5, 6.4, 6.6]

[INSERT FIGURE TS.1 HERE

Figure TS.1: Thermal specialization of species, sensitive to ocean acidification and hypoxia (A, left) causes warming induced distribution shifts (A, right). An example (B) is the northward expansion of warm-temperate species in the Northeast Atlantic. Differential distribution change across functional groups (C) will be influenced by species-specific impacts of future ocean acidification across phyla (D). Detailed introduction of each panel follows:

A) Mechanisms linking organism to ecosystem response explain the why, how, when, and where of climate sensitivity (blue to red color gradients illustrate transition from cold to warm temperatures). As all biota, animals specialize on limited temperature ranges, within which they grow, behave, reproduce, and defend themselves by immune responses (left). Optimum temperatures (T_{opt}) indicate performance maxima, pejus temperatures (T_p) the limits to long-term tolerance, critical temperatures (T_c) the transition to anaerobic metabolism, and denaturation temperatures (T_d) the onset of cell damage. These thresholds can shift by acclimatization (horizontal arrows). Under elevated CO_2 levels and in hypoxic waters performance levels can decrease and windows of performance be narrowed (dashed green arrows pointing to dashed black curves). Shifts in biogeography result during climate warming (right). The polygon delineates the range in space and time, the level of grey denotes abundance. Species display maximum productivity in southern spring, wide seasonal coverage in the center, and a later productivity maximum in the North. The impact of photoperiod increases with latitude (dashed arrow). During warming, the southern temperature and time window contracts while the northern one dilates (directions and shifts indicated by arrows). Control by water column characteristics or photoperiod may overrule temperature control in some organisms (e.g., diatoms), causing contraction of spatial distribution in the north. B) Long-term changes in the mean number of warm-temperate pseudo-oceanic species in the Northeast Atlantic from 1958 to 2005. C) Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, with number of observations and significance (*p<0.1, **p<0.05, ***p<0.01). D) % fraction of studied scleractinian coral, echinoderm, molluscan, crustacean, and fish species affected negatively, positively, or not at all by various levels of ambient CO_2. Effects considered include those on life stages and processes reflecting physiological performance (O_2 consumption, aerobic scope, behaviors, scope for behaviors, calcification, growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, morphology). Horizontal bars above columns represent frequency distributions significantly different from controls. [Figures 6-7, 6-10, 6-11, and 30-11]]

Rising atmospheric CO_2 not only causes ocean warming but also changes in carbonate chemistry termed ocean acidification. Ocean acidification has ramifications for processes ranging from physiology and behavior to population dynamics (*medium* to *high confidence*). A wide range of sensitivities to projected acidification exists within and across organism phyla (Figure TS.1). Across organisms, sensitivity decreases with increasing capacity to compensate for the elevated internal CO_2 concentration or falling pH (*medium confidence*). Most plants including algae respond positively to elevated CO_2 levels by increasing photosynthesis and growth (*high confidence*). Limits to adaptational capacity remain unexplored. See also Box TS.9. [6.2.2, 6.2.3, 6.2.4, 6.2.5, 6.2.6, 6.3.4, Box CC-OA]

Field observations attributed to anthropogenic ocean acidification are few due to limited changes in water chemistry between preindustrial times and today. Shell thinning in planktonic foraminifera from various regions and Southern Ocean pteropoda has been attributed fully or in part to acidification trends (*medium confidence*). Coastward shifts in upwelling regimes of the Northeast-Pacific and upwelled CO_2-rich waters presently causing larval oyster fatalities in aquacultures (*high confidence*) or shifts from mussels to fleshy algae and barnacles (*medium confidence*) provide an early perspective on future effects of ocean acidification. Ecosystems at risk of ocean acidification are warm and cold water coral reefs (*high* or *medium confidence*). [6.1.2, 6.2.2, 6.2.5, 6.3.4]

Climate change has influenced ocean primary productivity, with positive consequences for some fisheries and negative ones for others (*medium confidence*). The catch potential of fisheries has increased in some regions and decreased in others with consequences for the food and livelihood of involved human communities (*high confidence*). Fisheries at high latitudes are showing increased productivity due to sea ice retreats and increases in net primary productivity. In other regions, stratification of the water column driven by warming has reduced net primary productivity of the ocean. [18.3.4, 18.4.1, 18.5.7]

The ongoing expansion of hypoxic regions termed Oxygen Minimum Zones or anoxic "dead" zones constrains the habitat of oxygen-dependent animals, plants, and microbes while it benefits anaerobic microbial life (*high confidence*). Warming-induced stratification, reduced intensity of ocean circulation, and the decomposition of organic matter by heterotrophic organisms create an expansion of these specialized, microbially dominated ecosystems. The removal of fixed nitrogen (denitrification) via the metabolism of selected bacteria and archaea can

reduce nutrient inventories and alter the nitrogen-phosphorus balance. Hypoxia tolerance varies among species and is influenced by temperature, elevated CO_2, food consumption, and oxygen demand. [6.2.2, 6.2.3, 6.2.4, 6.2.5, 6.2.6, 6.3.3, 6.3.5, 18.3.4]

Specific regional examples include the following. See also Table TS.1.

- In Europe, observed warming has shifted the ranges of marine fishes to higher latitudes (*high confidence*) and reduced body size (*low confidence*). Observed higher water temperatures have adversely affected both wild and farmed freshwater salmon production (*high confidence*). [23.4.6]
- In the Northeastern Atlantic, High Latitude Spring Bloom systems are responding to rapid warming with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages and the reorganization of fish assemblages (*high agreement, medium evidence*). The abundance of boreal species has decreased along the southern fringe and increased along the northern fringe. However, substantial natural variability over the past 30 years has occurred in the entire Northeast Atlantic region as part of the Atlantic Multidecadal Oscillation. These changes have both positive and negative implications for the future of the fisheries within the High Latitude Spring Bloom systems. [6.3.2, 30.5.1, 30.8.3, WGI AR5 Chapter 14]
- The upper layers of the world's Semi-Enclosed Seas show significant warming since 1982, although this warming signal is strongly influenced by long-term variability (e.g., Atlantic Multidecadal Oscillation) (*medium confidence*). Further warming will *very likely* cause greater thermal stratification, reducing oxygen levels at depth and extending hypoxic zones, especially in the Baltic and Black Seas. These changes are *likely* to impact regional ecosystems and fisheries, tourism, and other human activities, although the understanding of the potential impacts is relatively undeveloped. [30.3, 30.5.6]
- An increased nutrient supply through intensified upwelling in some regions (through intensified upwelling) threatens deep sea ecosystems with hypoxia by increasing the rate of metabolism (and hence oxygen use) (*medium agreement, medium evidence*). Similarly, a decrease in primary productivity in some areas (e.g., subtropical gyres) may reduce the availability of organic carbon to deep sea ecosystems. These changes are *virtually certain* to increase due to the amplifying influence of rising deep water temperatures on microbial metabolism. [30.5.7, 6.1.1]

Food production systems and food security

The effects of climate change on food production are already evident in several regions of the world (*high agreement, medium evidence*). Negative impacts of climate trends have been more common than positive ones, although the latter predominate at high latitudes (*high confidence*). Yields have increased in some (mid to high latitude) regions, due to warming and higher CO_2 (*low confidence*), and decreased in other (mainly low latitude) regions due to water shortages and higher temperatures (*medium confidence*). Since AR4, there have been several periods of rapid food price increases, demonstrating the partial sensitivity of current markets to climate variability. These recent price changes cannot presently be attributed to climate change, due to the presence of other drivers. Social and economic issues such as energy policy and changes in household income will remain the main drivers of changes in food security in the near-term, regionally and locally. [7.2, Figures 7-2, 7-3, 7-4, Table 7-1, 18.4.1, Table 18-9]

There is new understanding since AR4 of the sensitivity of crops to extreme heat, which reinforces the importance of temperature changes for determining impacts of climate change on regional crop yields (*medium agreement, medium evidence*). Extreme heat also has a negative effect on food quality in terms of nutrition and processing (*high agreement, robust evidence*). Evidence since AR4 confirms the positive effects of CO_2 and negative effects of elevated tropospheric ozone on crop yields (*high confidence*). There is emerging experimental and modeling evidence that interactions among production factors such as CO_2 and ozone, mean temperature, extremes, water, and nitrogen can alter primary food production in complex ways (*high agreement, medium evidence*). [7.2, 7.3, 7.3.2, 7.4, Figures 7-2, 7-5, 7-6, and 7-7]

Specific regional examples include the following. See also Table TS.1.

- In Africa, livelihood-based approaches for managing risks to food production from multiple stressors, including rainfall variability, have increased substantially since 2007 (*high confidence*). Collaborative, participatory research including scientists and farmers, strengthened communication systems for

anticipating and responding to climate risks, and increased flexibility in livelihood options strengthen agricultural coping strategies for near-term climate variability and provide potential pathways for increasing capacities to adapt to climate change. [22.4.5, 22.4.6, 22.6.1]

- In Europe, yields of some arable crop species such as wheat have been negatively affected by observed warming in some countries since the 1980s (*medium confidence*). [23.4.1]
- Food security of many indigenous and rural residents in the Arctic is being impacted by climate change, for example affecting indigenous people's access to traditional foods that have provided sustenance, cultural, religious, economic, and community well-being for many generations (*high confidence*). [28.2.4, 28.2.7, 28.4.1]

Urban areas

Many urban areas have long been exposed to a range of hazards and disaster risks that could be exacerbated by climate change (*high confidence*). These include water shortages and droughts in urban regions, geo-hydrological hazards, inland and coastal flooding, windstorms and storm surges, high levels of air pollution, extremes in urban heat and cold and urban heat islands, and novel compound and slow onset hazards that impact ecosystem resilience. Reducing basic service deficits and building resilient infrastructure systems could significantly reduce global climate risk (*very high confidence*). [8.2, 8.3]

Around one billion people live in informal settlements in urban areas with inadequate or no provision for infrastructure and services that provides a foundation for adaptation (*high confidence*). Here, poverty and social inequality may be aggravated by climate change and the lack of adaptive capacity. The adaptive capacity of an urban center is much influenced by the quality and coverage of infrastructure (piped water supplies, sewers and drains, all-weather roads, and electricity provision) and services that include solid waste collection, policing, health care, emergency services, and measures to reduce disaster risk. The extent to which urban and higher levels of governments are able to mobilize resources and choose the most appropriate technical and institutional systems for service delivery influences adaptive capacity and deepens climate resilience. The rate and magnitude of urban development in some low- and middle-income countries also bring great challenges that many high-income nations do not have to deal with. [8.2, 8.3]

Specific regional examples include:

- In North America, several social and economic impacts observed in human settlements have been attributed, with different degrees of certainty, to climate-related processes (*high confidence*), including but not limited to sea-level rise, changes in temperature and precipitation, and occurrences of extreme events such as droughts and storms. Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific social and environmental factors and processes, with some (e.g., the legacy of previous and current stresses) common to urban and rural settlements. In cities, concentrations of populations, economic activities, cultural amenities, and built environments in highly-exposed urban locations such as coastal and dry areas create higher hazard risks. For example, Mexico City is vulnerable due to the high density of population combined with several socio-economic and environmental sources of vulnerability. [26.8]

Rural areas

Rural areas still account for almost half the world's population and about 75% of the developing world's poor people. There is a lack of clear definition of what constitutes rural areas, and definitions that do exist depend on definitions of the urban. Across the world, the importance of peri-urban areas and new forms of rural-urban interactions are increasing. However, rural areas, seen as a dynamic spatial category, remain important for assessing the impacts of climate change and the prospects of adaptation. [9.1.1, 9.1.2, 9.1.3]

Cases in the literature of observed impacts on rural areas often suffer from methodological problems of attribution, with regard to the difficulties of attributing extreme events to climate change, the status of local knowledge, and the action of non-climate shocks and trends, but evidence for observed impacts, both of extreme events and other categories, is increasing (*medium confidence*). Impacts attributable to climate change

include declining yields of major crops, extreme events such as droughts and storms, and geographically-specific impacts such as glacier melt in the Andes. [9.3.2]

Climate change in rural areas will take place in the context of many important economic, social, and land-use trends (*very high confidence*). In different regions, rural populations have peaked or will peak in the next few decades. The proportion of the rural population depending on agriculture is extremely varied across regions, but declining everywhere. Poverty rates in rural areas are falling more sharply than overall poverty rates, and proportions of the total poor accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising. [9.3.1]

In developing countries, rural people are subject to multiple non-climate stressors, including under-investment in agriculture (though there are signs this is improving), problems with land policy, and processes of environmental degradation (*high* to *very high confidence*). Hunger and malnutrition remain prevalent among rural children in South Asia and Sub-Saharan Africa. In developing countries, the levels and distribution of rural poverty are affected in complex and interacting ways by processes of commercialization and diversification, food policies, and policies on land tenure. In industrialized countries, there are important shifts towards multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors, and a change from subsidy-based to investment-based policy. [9.3.1, Table 9-1]

Prevailing development constraints, such as low levels of educational attainment, environmental degradation, gender inequality, and remoteness from decisionmakers, create additional vulnerabilities to climate change (*high confidence*). There are low levels of agreement on some of the key factors associated with vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, and integration into world markets. There is greater agreement on the importance for resilience of access to land and natural resources, flexible local institutions, and knowledge and information, and on the association of gender inequalities with vulnerability. Specific livelihood niches such as pastoralism and artisanal fisheries are vulnerable and at high risk of adverse impacts (*medium* to *high confidence*), partly due to neglect, misunderstanding, or inappropriate policy towards them on the part of governments. Lack of supportive policies in rural areas can reinforce existing vulnerability. [9.2, 9.3.5, 9.4.4]

Specific regional examples include:

- In North America, geographic isolation and institutional deficits are key sources of vulnerability for many small rural areas. [26.8]

Key economic sectors and services

Extreme climate events have impacted natural and physical livelihood assets, incomes, public health, and social institutions. For example, flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, but with a documented contribution of climate change and variability in some cases. [10.3.1, 10.7.3, 18.4.4, 18.4.7]

Climate change strongly affects insurance systems (*high agreement, robust evidence*). More frequent and/or intensive weather disasters increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. [10.7]

Specific regional examples include the following. See also Tables TS.1 and TS.2.

- In Europe, direct economic river flood damages have increased over recent decades (*high confidence*), but this increase is due to development in flood zones and not observed climate change. Some areas show changes in river flood occurrence related to observed changes in extreme river discharge (*medium confidence*). [23.2.3, 23.3.1, SREX 4.5]
- In North America, slow-onset perils such as sea level rise, drought, and permafrost melt are an emerging concern for some economic sectors, with large regional variation in awareness (*medium confidence*). [26.7]

Human health

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changing incidence in temperature and humidity extremes and occurrence of floods, storms, droughts, and fires. Indirectly, health may be damaged by ecological disruptions brought on by climate change (crop failures, shifting patterns of disease vectors), or social responses to climate change (such as displacement of populations following prolonged drought). Variability is a risk factor in its own right – it is more difficult to protect human health in a highly variable climate than one that is more stable. There is emerging evidence of non-linearities in response (such as greater-than-expected mortality due to heat waves) as climates become more extreme. [11.3, 11.5]

In recent decades, climate change has contributed to levels of ill-health (*likely*) though the present world-wide burden of ill-health from climate change is relatively small compared with other stressors on health and is not well quantified. Changes in temperature, rainfall, and sea-level have altered distribution of some disease vectors, increased heat wave casualties, and reduced food production for vulnerable populations (*medium confidence*). Dengue fever and malaria have increased in several regions of the world over the past few decades, but there is *very low confidence* in attribution of these trends to climate change. Although new infections and other conditions may emerge under climate change (*low confidence*), the largest risks by far will apply in populations already most affected by climate-related diseases. [11.3, 11.4, 18.4.5]

In addition to their implications for climate change, essentially all the important climate altering pollutants aside from CO_2 have other health implications (*very high confidence*). In 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants (*high confidence*), accounting potentially for an economic impact of 1-2 US$ trillion, depending on the economic valuation method used (*low confidence*). [Box 11.4]

Specific regional examples include the following. See also Table TS.1.

- In Africa, climate change is a multiplier of existing vulnerabilities affecting health outcomes, including water and sanitation coverage, food security, and access to health care and education (*high confidence*). [22.3.5]
- In Europe, climate warming has adversely affected trends in ground level tropospheric ozone (*low confidence*). [23.6.1]
- In Central and South America, climate variability and climate change are negatively affecting human health, either by increasing morbidity, mortality, and disabilities (*very high confidence*), through the emergence of diseases in regions previously non-endemic, or through the re-emergence of diseases in areas where they have previously been eradicated or controlled (*high confidence*). Climate-related drivers have been recognized for respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), Hantaviruses and Rotaviruses, pregnancy-related outcomes, diabetes, chronic kidney diseases, and psychological trauma. [27.3.7]

Human security

Mobility is a widely used and often effective strategy to maintain livelihoods in response to social and environmental changes (*high agreement, medium evidence*). There is *robust evidence* that migration and mobility are adaptation strategies to climate variability. People who lack the ability to move will face higher exposure to weather-related extremes in both rural and urban areas in the developing world. There is some evidence to suggest that expanding opportunities for mobility reduce vulnerability and enhance human security. Observations of implementation of planned resettlement show that legitimate and inclusive planning processes help alleviate the conflict and insecurity that individuals and communities may experience. [12.4.3]

Some of the factors that increase the risk of violent conflict including civil wars are sensitive to climate change (*medium agreement, medium evidence*). The evidence on the direct effect of climate change and variability on violence is contested. [12.5] Though there is little agreement about causality, there is *robust evidence* that shows that low per capita incomes, economic contraction, and inconsistent state institutions are associated with the

incidence of civil wars. These factors are sensitive to climate change. Climate change policy responses, particularly those associated with changing property rights to land, water, and resources, can increase the risk of violent conflict. A range of policies and institutions at multiple scales has been demonstrated to reduce the effects of environmental change on the risk of violent conflict. Economic growth, high per capita incomes, strong democratic institutions, social protection during economic and climate shocks, and robust institutional structures that protect property rights and manage conflict all reduce the risk that climate variability and extremes will lead to violence. [12.5]

Challenges for vulnerability reduction and adaptation are particularly high in regions that have shown severe difficulties in governance (*high confidence*). People living in places affected by violent conflict are particularly vulnerable to climate change (*high agreement, limited evidence*). Large-scale violent conflict harms infrastructure, institutions, natural capital, social capital, and livelihood opportunities. Since these assets facilitate adaptation to climate change, there are strong grounds to infer that conflict drives vulnerability to climate change impacts. [12.5.2, 19.6.1]

Currently many indigenous peoples are politically and economically marginalized and live in regions or depend on natural resources that are highly sensitive to climate changes (*high agreement, robust evidence*). Indigenous peoples have adapted to highly variable and changing social and ecological conditions. The current rate and magnitude of change will increasingly constrain the efficacy of indigenous and traditional knowledge in adaptive responses. [12.3]

Specific regional examples include the following. See also Table TS.1.

- In Europe, climate change has already affected cultural heritage (*low confidence*). [23.5.4, Table 23.6]
- In both Australia and New Zealand, indigenous peoples have higher than average exposure to climate change due to a heavy reliance on climate-sensitive primary industries and strong income and social connections to the natural environment, and face particular constraints to adaptation (*medium confidence*). Social status and representation, health, infrastructure and economic issues, and engagement with natural resource industries constrain adaptation and are only partly offset by intrinsic adaptive capacity (*high confidence*). Some proposed responses to climate change may provide economic opportunities, particularly in New Zealand related to forestry. Torres Strait communities are vulnerable even to small sea level rises (*high confidence*). [25.3, 25.8.2]
- For North America, indigenous peoples are vulnerable, due to their unique history and relationship to the land (*high confidence*). [26.8]
- Climate impacts on Arctic indigenous groups have been detected and attributed to climate change. These include changes in seasonal migration and hunting patterns, health, and cultural identity (*medium confidence*). [18.4.7, Box 18-5, 18.5.7, Table 18-9]

Livelihoods and poverty

Climate change constitutes an additional burden to the rural and urban poor. It acts as a threat multiplier, often with negative outcomes for livelihoods (*very high confidence,* based on *high agreement, robust evidence*). Weather events and climate, ranging from subtle shifts in trends to extreme events, affect poor people's lives directly through impacts on livelihood assets, such as losses in crop yields, destroyed homes, food insecurity, and loss of sense of place, and indirectly through increased food prices and climate policies. Changing climate trends provoke shifts in rural livelihoods such as from crop-based to mixed livestock- and forest-based livelihoods or to wage-based labor in agricultural and urban employment. Urban and rural transient poor who face multiple deprivations slide into chronic poverty as a result of weather events or extreme events, or a series of events, when they are unable to rebuild their eroded assets (*high agreement, limited evidence*). Many weather events that affect poor people remain unrecognized, such as short periods of extreme temperature or minor changes in the distribution of rainfall, due to short time series and geographically sparse, aggregated, or partial data, inhibiting detection and attribution in many low-income countries. [13.2.1, 13.3]

Climate change worsens existing poverty, exacerbates inequalities, and triggers new vulnerabilities and some opportunities. Poor people are poor for different reasons and thus are not all equally affected, and not all vulnerable people are poor. Climate change interacts with non-climatic stressors and entrenched structural inequalities to shape vulnerabilities (*very high confidence,* based on *high agreement, robust evidence*). Socially

and geographically marginalized people exposed to persistent inequalities at the intersection of gender, age, race, class, caste, indigeneity, and (dis)ability are particularly negatively affected by weather events and climate (see Box TS.4). Context-specific conditions of marginalization shape differential vulnerability. Preexisting gender inequalities are increased or highlighted by weather events and climate. Gendered impacts depend on customary and new roles in society, often entailing higher workloads, occupational hazards indoors and outdoors, psychological and emotional distress, and mortality in climate-induced disasters. Very scarce evidence exists that demonstrates positive impacts of climate change on the poor, including flood preparedness, collective action, institutional change, and social asset accumulation. Often, the more affluent can better take advantage of shocks and crises, given their flexible assets and power status. [13.1.2, 13.1.3, 13.2.1]

Despite known vulnerabilities and increasing exposure to climatic stressors, impacts of climate change on human livelihoods have rarely been detected with confidence. Such detection is complicated by the effects of other economic and social factors. There is emerging literature on the impact of climate on poverty, working conditions, violent conflict, migration, and economic growth, but evidence for detection or attribution remains *limited*. [18.4.3, 18.4.6, 18.4.7]

Information needs and methods

Significant improvements have been made in the amount and quality of climate data available for establishing baseline reference states of climate-sensitive systems. These include new and improved observational datasets, rescue and digitization of historical datasets, and a range of improved global reconstructions of weather sequences. The uncertainties inherent in climate model projections of regional climate changes have not decreased from AR4; in some cases, the addition of regional forcings (e.g., topography) have increased some uncertainties. [21.3.3, 21.5.3]

Specific regional examples include:

- **In Asia, there are regions that are not sufficiently represented in studies of observed climate change, in particular Central and West Asia.** Numerical data on trends in precipitation are hard to find compared to trends in temperature. Furthermore, research data on changes in extreme climate events do not cover most Asian regions. Studies of both observed and projected impacts on biodiversity, boreal forest dynamics, CO_2 fertilization of crops and plants, and urban settlements are limited. More trans-disciplinary research is needed on direct and indirect health effects from climate change impacts on air and water quality and water quantity in different parts of Asia. The vulnerability, impacts, and adaptation of aggregated household welfare, livelihoods, and poverty need to be adequately studied. [24.8]

A.ii. Adaptation Experience

Human and natural systems respond to climate and its effects. Natural systems have some potential to adapt, and are adapting, through ecological and evolutionary processes, and humans may intervene to promote particular adjustments. Responses in human systems include coping with climate variability and extremes and managing risks through planned adaptation to climate change impacts. Adaptation can be motivated by broader vulnerability-reduction and development objectives, such as reducing existing adaptation deficits to current climate. [14.1]

Adaptation activity is increasing and becoming more integrated within wider policy frameworks (*high confidence*). Adaptation planning is transitioning from a phase of awareness and promotion to the construction of concrete responses in societies (*high agreement, robust evidence*). National-level plans and adaptation strategies for developed countries are mentioned in the literature more than for developing countries, whereas more implementation cases are documented at the local level in developing countries. [14.3.4, 14.4.2, 15.2, 15.3.1]

The social dimensions of adaptation have attracted more attention, including the relationship between adaptation, development, and disaster risk management (*high agreement, robust evidence*). Attention to climate change impacts and disaster risk management, which are key elements of adaptation planning, appears to have a more prominent role in developed countries. Risk reduction, especially for developed countries, has been planned by a top-down approach including engineered infrastructure-based solutions such as dikes to prevent flooding and

coastal inundation and dams to improve water supplies. In contrast, there is a trend to link adaptation planning to development needs and stresses in developing countries. Strategies adopted in developing countries, e.g., those in NAPAs, are almost identical with standard development projects. [15.2, 15.3.1]

Adaptation assessments continue to evolve, and most include both top-down assessments of biophysical climate change risks and bottom-up assessments of what makes people vulnerable to those risks (*high confidence*). Most of the assessments of adaptation done so far have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation and evaluation of actual adaptation actions. The numerous assessments have led to a general awareness among decisionmakers and stakeholders of climate risks and adaptation needs and options, but this is often not translated into the implementation of even simple adaptation measures within ongoing activities or risk management planning. To overcome this "adaptation bottleneck," assessments may need to be linked more directly to particular decisions and the information tailored to facilitate the decision making process. [14.5.3, 14.5.4]

Evaluation of adaptation effectiveness is still in its infancy (*high confidence*). The demand for metrics to measure adaptation needs and effectiveness is increasing as more resources are directed to adaptation. But the search for metrics for adaptation will remain contentious with multiple alternatives competing for attention as governments, institutions, communities, and individuals value needs and outcomes differently and many of those values cannot be captured in a comparable way by metrics. These indicators need to track not just process and implementation, but also the extent to which targeted changes are occurring. [14.6.2, 14.6.3, 14.6.4]

A variety of tools are being employed in adaptation planning and implementation depending on social and management context (*high agreement, robust evidence*). Multidisciplinary efforts have been engaged to develop, assess, and communicate climate information and risk assessments across timescales. These efforts use a mixed portfolio of products from simple agroclimate calendars to computerized decision-support tools. Monitoring and early warning systems play an important role in helping to adjust adaptation implementation, especially on the local scale. [15.2.4]

The national level plays a key role in adaptation planning and implementation, while adaptation responses have diverse processes and outcomes at national, subnational, and local levels (*high agreement, robust evidence*). National governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy frameworks, creating legal frameworks, actions to protect vulnerable groups, and financial support to other levels of government. The number of adaptation responses has increased at the local level in developed and developing countries. However, there is a common trend that local governments are hindered by the absence of applicable guides to adaptation decision-making. Local councils and planners are often confronted by the complexity of adaptation, and even when information is available, they are left with a portfolio of options to prepare for future climatic changes and the potential unanticipated consequences of their decisions. Therefore, linkages with national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders, are important. [15.2.2]

The diversity of adaptation experience, including corresponding constraints and opportunities, can be seen in specific geographic contexts:

- **The scale and concentration of urban climate risk and hence the imperative for adaptation are being acknowledged, but responses are weak except for a handful of cities largely in high-income countries (*medium confidence*, based on *high agreement, medium evidence*).** City governments are slowly learning from adaptation implementation experience. Most current adaptation action focuses on low-cost interventions such as infrastructure and asset-creation as a co-benefit of existing development interventions. Examples of adaptation actions have often included the designation of a unit within city government with responsibility for adaptation, measures to involve key sectors so they understand why they need to engage with adaptation, the importance of local champions to initiate measures and ensure continuity, and the importance of dialogue and discussion with all key stakeholders. [8.3, 8.4, 8.5]
- **There is also recognition of the need to review building codes, infrastructure standards, and land-use management thereby developing scalable approaches to local adaptation planning (*medium confidence*, based on *high agreement, medium evidence*).** The weak emphasis on human, institutional, and ecological adaptation with long-term resilience building potential is a matter of concern. [8.3, 8.4, 8.5]

- **City-based disaster risk reduction is a strong foundation around which to build urban climate resilience (*high confidence*, based on *high agreement, medium evidence*).** The capacity to integrate climate risk, disaster risk reduction, and urban infrastructure and planning is being slowly built in some parts of the world. Locally-relevant adaptation plans, data, and feedback mechanisms are important for building urban resilience (*high agreement, medium evidence*). Improved feedback, monitoring, and reporting capacity supported by new generation risk screening, vulnerability mapping, and integrated urban climate assessment tools are helping catalyze social-learning to help mainstreaming. [8.2, 8.3, 8.4]
- **There is a growing body of literature on successful adaptation in rural areas, including documentation of practical experience (*high confidence*).** Gender, the supply of information for decision-making, and the role of social capital in building resilience are all key issues. Constraints to adaptation come from lack of access to credit, land, water, technology, markets, and information, and constraints are particularly pronounced in developing countries. [9.4.1, 9.4.3, 9.4.4]
- **In all regions of Africa, national governments are initiating governance systems for adaptation and responding to climate change (*high agreement, medium evidence*).** While a wide range of adaptation options, approaches, and decision tools are being tested and implemented at different scales across Africa, these have not yet been taken to a scale that would address the complex vulnerabilities and needs identified. Institutional frameworks cannot yet effectively coordinate the range of adaptation initiatives being implemented, resulting in a largely ad hoc and project-level approach, which is often donor-driven and may not result in local or national ownership (*medium agreement, medium evidence*). Efforts such as disaster risk reduction, social protection, adaptation technologies, climate-resilient infrastructure, ecosystem restoration, and livelihood diversification are reducing vulnerability and enhancing resilience, but this is still largely confined to local scales and isolated initiatives (*high agreement, medium evidence*). Institutional capacities and governance mechanisms need to be strengthened with respect to the ability of national governments and scientific institutions in Africa to absorb and effectively manage funds allocated for adaptation (*medium confidence*). [22.4.4, 22.4.5, 22.6.2]
- **In Europe, adaptation policy has been developed at international (EU), national, and local government level, but so far evidence relates to studies of the prioritization of options, and there is limited systematic information on current implementation (or effectiveness).** Some adaptation planning has been integrated into coastal and water management, as well as disaster risk management. There is little evidence of adaptation planning in rural development or land-use planning. Conservation policies and selection of protected areas have not considered so far impact of climate changes. [23.6.4, 23.7, Box 23-2]
- **In Australasia, adaptation is already occurring and adaptation planning is becoming embedded in planning processes, albeit mostly at the conceptual rather than implementation level (*high agreement, robust evidence*).** Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g., greening cities and recycling water) are already being implemented. Planning for sea-level rise and, in Australia, for reduced water availability is becoming widely adopted, although implementation of specific policies remains piecemeal, subject to political changes, and open to legal challenges. Adaptive capacity is generally high in many human systems, but implementation faces major constraints especially for transformative responses at local and community levels (*high confidence*). Constraints on implementation arise from: uncertainty of projected impacts; limited financial and human resources to develop and implement effective policies and rules; limited integration of different levels of governance; lack of binding guidance on principles and priorities; different values and beliefs relating to the existence of climate change and to objects and places at risk; and attitudes towards risk. [25.4, 25.10.3, Boxes 25-1, 25-2, and 25-9]
- **In North America, while different tiers of government are assessing their climate vulnerabilities and designing adaptation actions and programs, there has been more leadership in adaptation planning at the local level (*high confidence*).** Many governmental responses are in the diagnosis and planning stage and have not yet moved into implementation. Important barriers exist to effective adaptation such as path dependency, lack of assets and options, lack of funding and staff, lack of horizontal and vertical coordination, asymmetries in access to information, lack of social capital, and top-down decision making. There are few examples of proactive adaptation anticipating future climate impacts, and these are largely found in sectors with longer-term decision-making, including energy and public infrastructure. [26.7, 26.8, 26.9]

- **In the Arctic, indigenous people have a high adaptive capacity and have begun to develop novel solutions to adapt to climate changes combining traditional and scientific knowledge and co-producing climate studies with scientific partners.** [28.2.4, 28.2.7, 28.4.1]
- **Since AR4, the analysis and implementation of coastal adaptation has progressed significantly, but much more effort is needed for a transition towards climate resilient and sustainable coasts (*very high confidence*).** The analysis of adaptation has progressed towards novel approaches such as robust decision making and adaptation pathways that recognize that deep uncertainty in projections of drivers does not have to be a barrier to adaptation (*high confidence*). Adaptation analysis and implementation have also progressed towards considering the institutional context and governance of adaptation, albeit many governance challenges related to vertical and horizontal policy integration, political will, and power relations remain (*very high confidence*). Many countries, states/provinces, cities, and communities are now carrying out adaptation activities including the mainstreaming of coastal adaptation into relevant strategies and management plans. [5.5.2, 5.5.4]

Adaptation actions and approaches to reducing vulnerability and enhancing resilience can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management (see Table TS.3).

[INSERT TABLE TS.3 HERE
Table TS.3: Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.]

B) DECISIONMAKING IN A COMPLEX WORLD: UNDERSTANDING APPROACHES TO MANAGING RISKS THROUGH ADAPTATION

Managing the risks of climate change involves decisions with implications for future society, economies, environment, and climate. Some risks will emerge in the next few decades before substantial mitigation benefits can emerge, an era of climate responsibility. Other risks will emerge over a longer-term era of climate options; these risks vary across alternative climate change and development futures and depend on mitigation choices. The state of the future world cannot be known or projected with certainty (see Box TS.5), but robust decisions can be effective across a range of possible futures, especially if they build on existing knowledge. Fundamentally, responding to climate change can be considered an iterative process with continuing learning about risks and the effectiveness of risk management actions. Societies may need to transform in response to limits, for example by shifting goals or paradigms.

B.i. Determinants of risk

All decisions involving uncertainty and valued outcomes are risk assessments. Risk in the context of climate change is produced through the interaction of changing physical characteristics of the climate system with evolving characteristics of human, socioeconomic, and biological systems (exposure and vulnerability). See Figure TS.2. Alternative development paths influence risk both by changing the likelihood of physical impacts (through their effects on greenhouse gas emissions) and by altering vulnerability and exposure. [2.1.1, 19.1, 19.2, 19.2.4, Fig.19-1]

[INSERT FIGURE TS.2 HERE
Figure TS.2: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. Risks are a product of a complex interaction between physical hazards associated with climate change and climate variability on the one hand, and the vulnerability of a society or a social-ecological system and its exposure to climate-related hazards on the other. The definition and use of "key" and "emergent" are indicated in Section C.ii. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions. Changes in both the climate system (left side) and development processes (right side) are key drivers of the different core components (vulnerability, exposure, and physical hazards) that constitute risk. [19.1, Figure 19-1]]

B.ii. Principles for Effective Adaptation

Experience in the practice of adaptation serves to clarify the opportunities for, and the most significant barriers to, adaptation and the synergies and tradeoffs with other societal goals.

Among the many actors and roles associated with adaptation, those associated with local governance and with the private sector are increasingly recognized as critical to progress (*high confidence*). These two groups will bear the main responsibility for translating the top-down flow of risk information and financing, and for scaling up the efforts of communities and households in identifying and implementing their selected adaptation actions. Local institutions, including local governments, NGOs, and civil society organizations, are often limited by lack of resources and capacity. Private entities, from individual farmers and small to medium enterprises (SMEs) to large corporations, will seek to protect their production systems, supply lines, and markets, by pursuing adaptation-related opportunities. These goals will help expand adaptation activities, but they may not align with government or community priorities without coordination and incentives. [14.4.2, 14.4.3, 14.4.8]

In the presence of limited resources and a range of goals, adaptation implies trade-offs between alternative policy goals (*high confidence*). Economics provides important inputs to the evaluation and ranking of adaptation options in the face of uncertainty. Approximate approaches are often necessary because of the lack of data or because of uncertainties about the nature of climate change or the efficacy of adaptation actions. A range of economic tools helps to address these uncertainties and helps design policies that are acceptable with a range of preferences and robust to existing uncertainties. There are methodologies that are able to capture non-monetary

effects and distributional impacts, and to reflect ethical considerations. The resulting ranking depends on the "value system," i.e. on the weights attributed to different objectives. [17.2.6, 17.3, 17.5.4]

A range of factors constrains the planning and implementation of adaptation actions and potentially reduces their effectiveness (*high agreement, robust evidence*). The availability of resources for adaptation continues to feature strongly in the adaptation literature as a significant constraint on adaptation, as does uncertainty regarding future climate and disaster risk at national and regional scales. However, there is increasing awareness within the literature of the dynamics of social processes and governance that mediate the entitlements of actors to resources and promote social learning regarding adaptation. The manner in which these constraints manifest and their implications for the capacity of an actor to achieve adaptation objectives vary significantly across different regions and sectors as well as across different social and temporal scales. Some constraints to adaptation are a consequence of inherent trade-offs among different perceptions of risk and the allocation of finite resources, and therefore, adaptation efficiency and effectiveness may often be less than optimal. See Figure TS.3. Climate change policy at regional scales is constrained by the dual challenge in achieving integration at multiple administrative scales from global through national to local (multi-level governance), and across different sectors (policy coherence). The scales at which political decisions about climate change need to be made are frequently at odds with the definitions of regions. Climate change transcends political boundaries and is highly variable from region to region in terms of impacts and vulnerability. Likewise adaptation policies, options, and mitigation strategies are strongly region dependent and tied to local and regional development issues. [16.2, 16.3, 21.3]

[INSERT FIGURE TS.3 HERE
Figure TS.3: Key adaptation constraints assessed, categorized into two groups. One group reflects constantly evolving biophysical and socio-economic processes that influence the societal context for adaptation. These processes subsequently influence the second group of constraints affecting the implementation of specific adaptation policies and measures that could be deployed to achieve a particular objective. [Figure 16-2]]

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change (*medium confidence*). Such maladaptation can result from decisions where greater emphasis is placed on short-term outcomes ahead of longer-term threats, or from decisions that discount, or fail to consider, the full range of interactions arising from planned actions. [14.7.1, 14.7.2]

Cities are complex inter-dependent systems with potential synergies that could be leveraged to support adaptation (*high agreement, limited evidence*). Urban enterprises developed within globalized systems of production depend on reliable supply chains that may face particular difficulties. There are potential urban agglomeration economies around cost-effective adaptation and resilience building via improved built and ecological infrastructure and services and bringing together people, communities, and institutions to respond collectively (*medium confidence*, based on *medium agreement, limited evidence*). Thus, raising urban adaptive capacity requires effective multi-level governance with institutions that facilitate coordination across multiple, nested, and poly-centric authorities and have the capacity to mainstream adaptation measures. This is yet to be built in most parts of the world. [8.3, 8.4, 8.5]

Building human and institutional capacity for urban climate resilience will accelerate implementation and improve outcomes (*high confidence*). A binding constraint to effective and timely urban adaptation and building resilience is effective institutions and leadership across government, communities, civil society, knowledge institutions, and the media. There is evidence of expanding urban adaptation leadership, but building a wide support base for adaptation across many sectors, in and outside of government, to de-risk the impact of slow institutional development and leadership change is an important priority. This can be addressed by a number of structural interventions to enable city-wide alliances and frameworks to be built, institutionalization of processes, building a culture of exchange between learning organizations, and a strong emphasis on capacity building. Networking and sharing experiences among adaptation practitioners and between cities is also an important vehicle to improve city-level outcomes. [8.4, 8.5]

B.iii. Approaches for Managing Risks and Building Resilience in a Complex and Changing World

The report assesses a wide variety of approaches for managing risks and building resilience. Mitigation is assessed in WGIII AR5. Strategies and approaches to climate change adaptation include efforts to decrease vulnerability or exposure and/or increase resilience or adaptive capacity. Types of responses are given in Table TS.4.

[INSERT TABLE TS.4 HERE
Table TS.4: Entry points, strategies, measures, and options for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples given can be relevant to more than one category.]

Low-regrets actions to increase resilience

Strategies and actions can be pursued now that increase climate resilience while at the same time helping to improve human livelihoods, social and economic well-being, and responsible environmental management (*high confidence*). Adaptation actions can provide significant co-benefits such as alleviating poverty and enhancing development especially in developing countries. Climate change adaptation efforts can improve ecosystem resilience by implementing sustainable forestry quotas, expanding floodplain setbacks, implementing coastal afforestation and coral reef propagation, restoring degraded lands, maintaining healthy vegetation on slopes, incentivizing development away from coastal areas and bluffs, and removing barriers to the migration of plants and animals. [15.3.1, 17.2.7, 17.4.4, 20.6.2, 29.6.1, 29.6.2, Figure 29-5]

A low-regrets co-benefits approach of improving resilience through an emphasis on disaster risk reduction has become increasingly common (*high agreement, medium evidence*). Climate change adaptation and disaster risk reduction share similar objectives and challenges, although disaster risk management strategies by themselves often fail to account for a wide spectrum of threats and scales needed for climate change adaptation. There are many synergies between adaptation, development, and disaster risk reduction, and steps are being taken to achieve better integration (*high confidence*). [14.3.4, 14.4.2, 15.2.1, 15.2.3]

Building climate resilience in cities can be well-served by ecosystem-based adaptation with water and food systems as foci (*medium confidence*). Ecosystem-based adaptation is regarded as one of the more cost effective and sustainable approaches to urban adaptation, although the costs of needed land acquisition can be high. This is even though climate change will impact ecosystem services by altering ecosystem functions such as temperature and precipitation regimes, evaporation, humidity, and soil moisture levels. Ecosystem-based adaptation is closely linked to sustainable water management that ensures sufficient supplies, increases capacities to manage reduced freshwater availability, enables flood risk reduction and mitigation, manages waste water flows, and ensures water quality. [8.3, 8.5]

Integration and mainstreaming

Integration streamlines the planning and decisionmaking process and embeds climate sensitive thinking in existing and new institutions and organizations (*high confidence*). Integration helps avoid mismatches with development planning, facilitates the blending of multiple funding streams, and reduces the possibility of maladaptive actions. Development and adaptation can be complementary or competitive and development can yield adaptation co-benefits, provided it takes into account climate change in its design. Many aspects of economic development also facilitate adaptation to a changing climate, such as better education and health, and there are adaptation strategies that can yield welfare benefits even in the event of a constant climate, such as more efficient use of water and more robust crop varieties. Maximizing these synergies requires a close integration of adaptation actions with existing policies, referred to as mainstreaming. Mainstreaming adaptation into planning and decision-making, including official development assistance, is an opportunity for enhancing the effectiveness and efficiency of adaptation investments. [14.3.4, 14.4.2, 16.6, 17.2.7, 17.4.4]

Iterative approaches and learning

Due to the uncertainty, dynamic complexity, and short-to-long timeframes associated with climate change, robust adaptation efforts require iterative risk management strategies (*high agreement, medium evidence*). See Figure TS.4. Iterative risk management involves an ongoing process of assessment, action, reassessment, and response that may need to be applied under climate change, for decades, if not longer. [2.1.2, 2.2.1, 2.3.1, 15.2.3]

Adaptation planning and implementation is considered as a social learning process to formulate efficient plans, which allows periodical adjustments in order to reduce the uncertainty of the impacts of climate change and societal needs to cope with them (*high agreement, medium evidence*). Social learning is a relevant but under-investigated feature of planning and a critical part in the innovations for adaptation. Understanding of why and how learning takes place is needed to improve the impact and efficiency of plans, improve the transferability of best practices, increase public support, and translate learning into new plans. Monitoring and evaluation are two important learning tools in promoting this process. Although the importance of evaluation in adaptation is recognized, this topic is under-researched and requires significant work. [15.3.3]

[INSERT FIGURE TS.4 HERE
Figure TS.4: Schematic illustration of adaptation as an iterative risk management process. Each individual adaptation decision comprises well known aspects of risk assessment and management (top left panel). Each such decision occurs within and exerts its own sphere of influence, determined by the lead and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single correct adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations, and goals. [Figure 25-6]]

Working across scales

Opportunities exist for actors at all geographical and institutional levels and in different development contexts to facilitate, initiate, and implement effective adaptation action (*medium agreement, medium evidence*). Adaptation action at all levels—from households, firms, or municipalities to national government agencies and regional economic integration organizations—is influenced by resources made available by third parties, including the sharing of knowledge and information, the transfer of technologies, and the provision of financial resources. In addition, national and international public policy can encourage the preparation and implementation of national adaptation strategies. [16.6]

Adaptation governance plays a key role in promoting the transition from planning to implementation of adaptation (*high agreement, medium evidence*). The role of governance is highlighted in building adaptive capacity to climate change, in providing the connections among individuals, communities, organizations, agencies, and institutions at multiple levels, and in articulating top-down or bottom-up perspectives. Bottom-up approaches are particularly useful in efforts seeking to reduce social vulnerability and addressing adaptation to climate change as a process. However, adaptation to climate change also requires complementary top-down strategies through different levels of governments to realize mainstreaming adaptation. Adaptation planning also highlights the importance of intergovernmental and multidisciplinary approaches integrating science and planning. Because adaptation is a multidimensional issue involving many state and non-state actors functioning on varying scales of global, national, and local levels, a coordination of roles and responsibilities enhances institutional networking for effective implementation. Multilevel governance offers the chance to identify options for switching from reactive to proactive adaptation processes that are essential in safeguarding investments and infrastructures especially in urban adaptation. See Figure TS.5. [15.2.3, 15.4]

[INSERT FIGURE TS.5 HERE
Figure TS.5: Four main phases of adaptation planning and implementation: needs, planning, implementation, and evaluation. This is a cyclic, iterative process. Building capacity to respond to change, whether expected or unexpected, creates resilience in societies to cope in the face of uncertainties in climate change projections. Efforts in adaptation can be linked with development or disaster risk management. Adaptation governance underlies

capacity, and governance takes place at multiple scales: international, national, sub-national, and local. [Figure 15-1]]

Knowledge transfer

Information and knowledge on climate change risks from various stakeholders and organizations are essential resources for adaptation planning (*high agreement, robust evidence*). Although a wide range of adaptations are possible with current technologies and management practices, development and diffusion of technologies can expand the range of adaptation possibilities by expanding opportunities or reducing costs. [15.2.4]

Decision support situated at the intersection of data provision, expert knowledge and human decision-making across scales is most effective when it is context-sensitive, taking account of the diversity of different types of decisions, decision processes, and constituencies. [2.2, 2.3]

Traditional and indigenous forms of knowledge are a major resource for adapting to climate change except when the changes exceed the knowledge repertoire (*high agreement, robust evidence*). Culture and local and traditional forms of knowledge are highly dynamic and context dependent, reflecting and reasserting values and shaping both adaptive and maladaptive responses. Local and traditional knowledge is often neglected in policy and research, and mutual recognition and integration of local and traditional knowledge with scientific knowledge will increase the effectiveness of adaptation responses. [12.3]

Risk sharing mechanisms and economic instruments

Economic instruments have high potential in fostering adaptation as they directly and indirectly provide incentives for anticipating and reducing impacts (*high confidence*). Instruments comprise risk sharing and transfer mechanisms (insurance), loans including public private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including land taxes, direct investment, norms and regulations, behavioral approaches, and institutional innovations. Innovative fiscal instruments, measures to attract "climate-proof" public and private investment and micro-insurance coverage of poorer households, risk transfer mechanisms, and innovative market-based insurance coverage will be necessary to address the large climate adaptation finance needs. Markets provide an additional mechanism for adaptation (*high agreement, medium evidence*). [8.4, 10.7.4, 10.7.5, 10.7.6, 10.9, 17.4, 17.5]

Risk financing mechanisms at local, national, regional, and global scales contribute to increasing resilience to climate extremes (*medium confidence*). Applicable mechanisms comprise informal and traditional risk sharing, such as relying on kinship networks, as well as market-based instruments including microinsurance, insurance, reinsurance, and national, regional, and global risk pools. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially resilient insurance systems. With considerable disaster insurance market failure, public-private partnerships are the norm rather than the exception with the public sector acting as regulator, provider, or insurer of last resort (*high confidence*). Price signals associated with risk financing can provide incentives for reducing risk, yet the evidence of effectiveness is *limited* and the presence of many counteracting factors actually often leads to disincentives, also known as moral hazard. [10.7, 17.3.4, 17.3.6, 17.4, 17.5.1]

Transformation, including transformational adaptation

Adaptation options have focused mostly on cautious, incremental changes, but there is increasing recognition that transformative changes may be necessary as a response to projected climate changes (*medium confidence*). While no-regret, low-regret, and win-win strategies have attracted most attention in the past, there is increasing recognition that an adequate adaptive response will mean acting in the face of continuing uncertainty about the extent of climate change and the nature of its impacts and, thus, of adaptation needs. A focus on flexibility and adaptive management is becoming more common in selecting adaptation options. However, many see the need

for more transformative changes in perception and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems. [14.1, 14.3.4]

Transformation in wider political, economic, and social systems can either open up or close policy spaces for more resilient and sustainable forms of climate responses, particularly where contemporary development pathways are identified and addressed as part of the root causes of vulnerability. While transformations may be reactive, forced, or induced by random, stochastic factors, they may also be deliberately created. Deliberate transformations can take place across interacting spheres, the practical, political, and personal spheres of transformation (See Figure TS.6). Whether in relation to transformational adaptation, transformation to low-carbon societies, or transformations to global sustainability, attention to all three spheres is relevant in responding to the observed and anticipated impacts of climate change. Climate-resilient pathways may involve conflicting goals and visions for the future, and not every transformation is considered equally ethical, equitable, or sustainable. [20.5.2]

[INSERT FIGURE TS.6 HERE
Figure TS.6: The practical, political, and personal spheres of transformation. [20.5.2, Figure 20-2]]

B.iv. Understanding of Limits to Adaptation

Limits to adaptation emerge as a result of the interaction between climate change and other biophysical and socioeconomic constraints (*high agreement, robust evidence*). While biophysical thresholds represent an important determinant of limits to adaptation, particularly for natural systems, socioeconomic conditions and trends also contribute to the definition of limits in social systems. In particular, demographic change as well as economic development will influence future human vulnerability and adaptive capacity, but the externalities of these processes may reduce the resilience of natural systems to adapt to a changing climate. [16.2, 16.3, 16.4]

Evidence from both natural and human-managed systems demonstrates the existence of limits to adaptation to climatic and other related environmental and socio-economic risks (*high agreement, robust evidence*). Archeological and historical evidence is providing growing insights into periods of societal change, including catastrophic societal failures, in which climate change or variability may have been a contributory factor. Such evidence indicates that socioeconomic and cultural factors mediate societal responses to emergent risks such as changes in climate and influence the likelihood of limits to adaptation being reached and exceeded. [16.3, 16.5, 16.5.1, 16.5.2, 16.8, Box 16-3]

Social limits to adaptation are dynamic over space and time due to normative judgments and values of actors, technological change, and emergent properties of complex systems (*high agreement, limited evidence*). Limits to adaptation are expected to be exceeded locally before being exceeded regionally and at larger spatial scales. This should provide regional, national, and international actors with an early warning of possible future adaptation constraints and limits. Some adaptation limits may be removed over time either due to changing normative judgments and values of actors that lead to the abandonment of previously held objectives, or through technological advancement. However, some actors may find that transformational changes are required that necessitate trade-offs in some values in order to preserve others. [16.4.1, 16.4.2]

The greater the magnitude of climate change, the greater the likelihood that adaptation will encounter limits (*high agreement, limited evidence*). Mitigation and adaptation are complementary strategies. Greater adaptation efforts will be required to achieve the objectives of actors if mitigation efforts are not successful in avoiding high magnitudes of climate change. There are, however, limits to the extent to which adaptation could reduce the impacts not avoided by mitigation, and residual loss and damage may occur despite adaptive action. Knowledge about limits to adaptation could therefore inform the level and timing of mitigation and might justify early mitigation action. However, as the future capacity of actors in different sectoral and regional contexts to adapt to climate change remains uncertain, the implications of adaptation for mitigation demand will be contingent upon economic development pathways and investments made to enhance the adaptive capacity of vulnerable actors. [16.3.1, 16.5, 19.6, 19.7, 20.5.3]

Much of the literature identifying limits to adaptation for specific systems and/or management objectives is associated with biophysical systems, particularly ecosystems and/or individual species that are dependent

upon specific biophysical regimes (*high agreement, robust evidence*). Those species that already persist at the edge of their thermal and/or hydrological limits may be most vulnerable to a changing climate. Species do have capacity to adapt through phenotypic and genetic responses. The physiological and/or ecological thresholds imposed by climate effectively represent "hard" limits in that no adaptation options can be implemented to enable sustainability once thresholds are exceeded. As a broad range of human values and managed systems are dependent upon ecosystems goods and services, "hard" limits in ecological systems have the potential to constrain or limit adaptation in socioeconomic systems. [16.4.1]

The capacity to describe and predict limits to adaptation is significantly impaired by the complexity of socio-ecological systems (*high agreement, limited evidence*). While there is *high agreement* that limits to adaptation exist, detailed understanding of the level at which climate change impacts may impose an intolerable risk to social objectives (the definition of adaptation limits adopted here) is available only for a small number of ecosystems and crop species. Any assessment of limits to adaptation in human systems is preliminary because of uncertainty about the existence and level of adaptation limits, and whether these limits are hard or soft. Furthermore, social, economic, and cultural trends and conditions, including uncertainty regarding actors' objectives and values and how they evolve over time, further confound explicit definitions of limits. Thus, while climate change raises "reasons for concern" regarding the sustainability of various natural and human systems, there is little evidence to support climate thresholds, such as a 2°C increase in global mean temperature, as being robust definitions of limits to adaptation. [16.4.2]

Specific regional examples of limits to adaptation have been assessed:

- In Africa, growing understanding of the multiple inter-linked constraints on increasing adaptive capacity is beginning to indicate potential limits to adaptation (*high agreement, limited evidence*). Climate change combined with other external changes (environmental, social, political, technological) may overwhelm the ability of people to cope and adapt, especially if the root causes of poverty and vulnerability are not addressed. Risks of maladaptation are increased by development interventions that often fail to consider how different types of change interact and undermine the ability of people to cope with multiple stressors. Evidence is growing for the effectiveness of flexible and diverse development systems designed for reducing vulnerability, spreading risk, and building adaptive capacity, and for the benefits of new development trajectories that place climate resilience, ecosystem stability, equity, and justice at the center of development efforts. [22.4.6]
- For Europe, synthesis of evidence across sectors and subregions confirms that there are limits to adaptation from social, economic, and technological factors. Adaptation is further impeded because climate change affects multiple sectors. [23.5, 23.10]

_____ START BOX TS.5 HERE _____

Box TS.5: Characterizing the Future

While there are many possible scenarios for future climate change and societal development, current decisions narrow future options. New risks will emerge in the coming decades as a result of past emissions and current socioeconomic trends. Societal responses, particularly adaptations, will influence outcomes during this era of climate responsibility. In contrast, benefits of current mitigation efforts will emerge over a longer period. Future risks during this longer-term era of climate options are thus linked to current mitigation and development choices.

Trends in vulnerability, exposure, and climate, as well as weather and seasonal forecasting of climate variability, can inform decisions in the era of climate responsibility. Climate and impact model projections become increasingly relevant for climate-affected decisions playing out over the longer term, recognizing that uncertainties about future vulnerability and exposure also increase over time. [21.3.3, 21.5.1, 21.5.3]

Scenarios are a vital part of managing uncertainty. [2.2.1] Scenarios provide a mechanism for characterizing possible socioeconomic futures and climate change outcomes. Socioeconomic factors influence not only greenhouse gas emissions but also the size and location of populations at risk from various climate change impacts, the differential vulnerability of these populations, and their capacities to adapt.

Modeled future impacts assessed in this report draw on a combination of climate model simulations (CMIP3) using SRES scenarios and new climate model simulations (CMIP5, completed in 2011-12) using the new Representative Concentration Pathway (RCP) scenarios. The RCPs span the range of SRES scenarios for long-lived greenhouse gases, but they have a narrow range and fall at or below the lowest SRES in terms of emissions of ozone and aerosol precursors and related pollutants (*high confidence*). The IPCC has created and used emission scenarios to project future climate since the First Assessment Report, and most recently the SRES scenarios were used in the Third Assessment Report, AR4, and SREX. With AR5, the new RCP scenarios present both emissions and greenhouse gas concentration pathways, and corresponding socio-economic pathways have also been developed. The 4 RCPs assume different levels of mitigation, leading to 21st century radiative forcing levels of 2.6, 4.5, 6.0, and 8.5 W m^{-2} (see WGI AR5 Chapters 1, 6, 11, and 12). All RCPs project a rapid decline in short-lived pollutants and land-use change by 2050, almost independent of fossil-fuel use and population, while other published scenarios indicate a less rapid decline in aerosol precursors**.** A process (shared socioeconomic pathways, SSP's) has been initiated to identify shared assumptions and global scenarios for use in both mitigation and adaptation research. But although progress has been made, the vast majority of the impacts, adaptation, and vulnerability literature since AR4 continues to be based on the SRES. [1.1.3, 21.5.3]

Future climate depends on future climate forcing from emissions and concentrations, the climate system response to forcing, and the natural internal variability of the climate system (see Box TS.5 Figure 1). Climate models continue to produce a range of projected futures where for some variables and locations the sign of projected change may differ from one model to another. However, in many instances this indicates a lack of significant change compared to the natural variability for that region. The degree to which the model uncertainty can be reduced remains an open question. [21.5.3]

Box TS.5 Figure 1 illustrates alternative climate futures, under RCPs 4.5 and 8.5, along with observed temperature and precipitation changes. Future climate change interacts with vulnerability and exposure to determine future risks.

[INSERT BOX TS.5 FIGURE 1 HERE
Box TS.5 Figure 1: Changes in annual average temperature (A) and precipitation (B). For observations (top map, A and B; CRU), differences are shown over land between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For projections (bottom four maps, A and B; CMIP5), four classes of results are displayed. (1) White indicates areas where for >66% of models the annual average change is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions, more than 2/3 of models show no significant change in the annual average using this measure of significance, although this does not imply no significant change at seasonal or shorter time-scales such as months to days. (2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions, more than 2/3 of models show a significant change in annual average, but less than 2/3 agree on whether it will increase or decrease. (3) Colors with white circles indicate the change averaged over all models where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on whether the annual average will increase or decrease. In these regions, more than 2/3 of models show a significant change in annual average and more than 2/3 (but less than 90%) agree on whether it will increase or decrease. (4) Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether the annual average will increase or decrease. For models that have provided multiple realizations for the climate of the recent past and the future, results from each realization were first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios were calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065. See also Annex I of WGI AR5. [Box CC-RC]]

_____ END BOX TS.5 HERE _____

C) FUTURE RISKS AND CHOICES: RISKS AND POTENTIAL FOR ADAPTATION

Assessment of the full range of potential future impacts, not only the most likely outcomes, provides a basis for understanding future risks. In some cases, the probability of an impact occurring may be relatively low, but consideration is warranted because the potential consequences are significant. This section covers future risks across sectors and regions, and their sensitivity to the magnitude and rate of climate change, to the characteristics of development that affect vulnerability, and to policy choices. It emphasizes the importance of societal development in determining impacts at a given magnitude of climate change. It also recognizes that individuals vary in what they hold most dear, in how they value assets that are not typically monetized, and in how much they discount the future. The section examines the distribution of risks across populations with contrasting vulnerability and adaptive capacity, across sectors where metrics for quantifying impacts may be quite different, and across regions with widely varying traditions and resources. The assessment features interactions across sectors and regions and among climate change and other stressors. It elucidates how and when choices matter in reducing future risks and highlights the differing eras for mitigation and adaptation benefits.

C.i. Sectoral Risks with Regional Examples

For the era of climate responsibility (the next few decades) and the era of climate options (the longer term), risks will emerge across sectors and regions, dependent on the magnitude and rate of climate change and on the vulnerability of exposed social and natural systems.

Freshwater resources

Projected climate changes would change hydrological regimes substantially (*high agreement, robust evidence*). Runoff and groundwater recharge are projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions, controlled mainly by changes in precipitation. Changes in runoff are typically one to three times greater than changes in precipitation. Except in very cold regions, warming brings forward the snowmelt season, altering the seasonal regime. Figure TS.7 depicts projected decreases in groundwater resources and associated vulnerability. [3.4.5, 3.4.6]

Hydrological impacts of climate change increase with increasing greenhouse-gas emissions (*high agreement, robust evidence*). A low-emissions pathway reduces damage costs and costs of adaptation. Impacts of climate change on water resources are expected to reduce economic growth, particularly in developing countries (*high agreement, limited evidence*). [Table 3-2, 3.4, 3.5, 3.6.5]

Glaciers will continue to lose mass, with meltwater yields from stored glacier ice eventually diminishing as the glaciers shrink (*high agreement, robust evidence*). The rate of loss per unit of glacierized area will accelerate. The accumulation season will become shorter and the melting season longer, and in almost all regions total accumulation will decrease. In many regions meltwater production will increase during the next several decades but decrease thereafter. Glaciers have long response times and would continue to lose mass even if the climate were to cease to change. [3.4.4]

[INSERT FIGURE TS.7 HERE
Figure TS.7: Human vulnerability to climate-change-induced decreases of renewable groundwater resources by the 2050s for lower (B2) and higher (A2) emissions pathways and two global climate models. The higher the vulnerability index (percent decrease of groundwater recharge multiplied by a sensitivity index), the higher the vulnerability. The index is computed for areas where groundwater recharge is projected to decrease by at least 10%, as compared to the reference period 1961-90. [Figure 3-9]]

Climate change is projected to reduce renewable water resources in most semi-arid and arid regions, potentially affecting food security (*high agreement, robust evidence*). Drying of soils is projected in most dry regions (*medium confidence*). Projected changes in droughts depend partly on the definition of drought. [3.4.9, 3.5, WGI AR5 12.4.5]

Projected climate changes imply large changes in the frequency of floods (*high agreement, robust evidence*). More frequent intense rainfall events [WGI AR5 12.4.5] would increase the frequency of flooding in small catchments, but the implications for larger catchments are more uncertain because of the limited extent of the intense events. In some areas, reduced snowfall will reduce spring flood peaks. More people will be exposed to floods, notably in Asia, Africa, and Central and South America, and economic losses will increase due to both increased exposure and anthropogenic climate change (*high confidence*, based on *high agreement, limited evidence*). Vulnerability can be reduced by adaptation. [3.4.9]

Water quality changes are linked to warming, changes in rainfall, and climate-related erosion and deforestation (*high agreement, limited evidence*). Projections under climate change scenarios show a risk of deteriorating water quality for municipal supply, even with conventional treatment. Possible positive impacts include reduced risks of eutrophication and algal blooms when nutrients are flushed from lakes and estuaries by more frequent storms and hurricanes (*high agreement, limited evidence*). [3.2.5, 3.5.2]

Climate change increases investment costs for water and wastewater treatment, while operating costs could rise or fall. Improved or even new water-treatment infrastructure may be needed to address variations in the quantity and quality of water (*high agreement, medium evidence*), but under warmer conditions water and wastewater treatment processes may perform better (*low* to *medium agreement, limited evidence*). [3.5.2, 3.6]

Adaptive water management techniques offer an opportunity to address uncertainty due to climate change (*high agreement, limited evidence*). Such techniques include scenario planning, employing experimental approaches that involve learning from experience, and developing flexible solutions that are resilient to uncertainty. However, there are barriers such as lack of technical capacity, financial resources, awareness, and communication. [3.6.2, 3.6.6]

Adaptation to climate change in the water sector provides many opportunities for low-regrets improvements (*high agreement, limited evidence*). Of the global cost of adaptation, 85% is required in developing countries (*medium agreement, medium evidence*), in amounts similar to those estimated for the Millennium Development Goals. Annual global adaptation costs to maintain baseline levels of water-supply and sanitation services will be 50 to 70% of baseline investment in the sector (*high agreement, limited evidence*). Some adaptive water-management measures also mitigate climate change (*medium agreement, limited evidence*). For example, wetland conservation increases carbon storage. [3.6.1, 3.6.5, 3.7.2]

Specific regional examples include:

- In Africa, the impact of climate change on water availability is uncertain (*high confidence*). Water resources are subject to high hydro-climatic variability over space and time, and are a key constraint on the continent's continued economic development. Water is the primary medium through which early and subsequent climate change impacts will be felt by people, ecosystems, and economies. Many of the fragile terrestrial and aquatic ecosystems in Africa are implicitly or explicitly water dependent. Impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical socio-political and economic footprint. Strategies and plans of action to adapt to climate change through an integrated approach to land and water management benefit establishment of effective resilience to the projected impacts of climate change. [22.3.2, 22.3.3]
- In Europe, climate change will decrease surface water quality due to higher temperatures (*medium confidence*). [23.6.3]
- In Asia, water scarcity is expected to be a major challenge for most of the region due to increased water demand and lack of good management (*medium confidence*). Water resources are important in Asia given the massive population. However, there is *low confidence* in future precipitation projections at a regional scale and thus in freshwater availability in most parts of Asia. Shrinking of glaciers in Central Asia and the Himalayas is projected to affect water resources in downstream river catchments. Population growth and increasing demand arising from higher standards of living could worsen water security in many parts of Asia and affect many people in the future. Better water management strategies are needed to ease water scarcity. Water saving technologies and changing to drought tolerant crops have been found to be successful adaptation options in the region. [24.4.3, Box 3-1]
- In Australasia, freshwater resources are projected to decline in far south-west and far south-east mainland Australia (*high confidence*) and for rivers originating in the eastern and northern parts of New Zealand

(*medium confidence*). Systematic constraints on water resource use in southern Australia, driven by rising temperatures and reduced cool-season rainfall, have the potential to be severe but can be moderated or delayed significantly by globally effective mitigation combined with adaptation, with an increasing need for transformative adaptation for greater rates and magnitude of change (*high confidence*). Integrated responses encompassing management of supply, recycling, water conservation, and increased efficiency across all sectors are available but face implementation constraints. [25.2, 25.5.1, Box 25-2]

- Throughout North America, it is *very likely* that the 21st century will witness decreases in water quality, and increases in flooding and droughts under climate change, with these impacts exacerbated by other anthropogenic drivers. It will also witness decreases in water supplies for urban areas and irrigation in some areas of North America, with confounding effects of development, except in general for southern Mexico, the northwest and northeast coastal USA, and west and east Canada. [26.3, 26.8]
- In Central and South America, although there is high uncertainty in terms of climate change projections for regions with high vulnerability in terms of current water availability, this vulnerability is expected to increase in the future due to climate change impacts (*high confidence*). Already vulnerable regions in terms of water supply, like the semi-arid zones in Chile-Argentina, North Eastern Brazil, and Central America and the tropical Andes, are expected to increase even further their vulnerability due to climate change. Glacier retreat is expected to continue, and a reduction in water availability due to expected precipitation reduction and increased evapotranspiration demands is expected in the semi-arid regions of Central and South America. These scenarios would affect water supply for large cities, small communities, hydropower generation, and the agriculture sector. Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability. Constitutional and legal reforms towards more efficient and effective water resources management and coordination among relevant actors in many countries in the region (e.g., Honduras, Nicaragua, Ecuador, Peru, Uruguay, Bolivia, and Mexico) also represent an adaptation strategy to climate variability and change. [27.3.1, 27.6.1]

Terrestrial and inland water systems

There is *high confidence* for freshwater ecosystems and *medium confidence* for terrestrial ecosystems that direct human impacts such as land-use change, pollution, and water resource development will continue to dominate the threats to ecosystems, with climate change becoming an increasing additional stress through the century, especially for high-warming scenarios such as RCP 6.0 and 8.5. Model-based projections imply that direct land cover change will continue to dominate over climate-induced change for low to moderate warming scenarios at global scales (e.g., RCP2.6 to RCP6.0). However, in many areas not subject to intensive human disturbance, even lower levels of projected future climate changes will result in changes in large-scale ecosystem character depending on the nature of regional climate changes (*high confidence*). Such changes may not be fully apparent for several decades after reaching the critical regional climate state, due to long response times in ecological systems (*medium confidence*). For higher warming scenarios, some model projections imply climate-driven large-scale ecosystem changes that become comparable with direct human impacts at the global scale. [Box CC-RF, 4.3.3]

Significant feedbacks exist between terrestrial ecosystems and the climate (*medium confidence*). Thus local, regional, and global climate may be affected as ecosystems are altered, through climate change itself or other mechanisms, such as conversion to agriculture or human settlement. These climate feedbacks are driven by changes in surface albedo, evapotranspiration, and greenhouse gas emissions. The regions where the climate is affected may be different from the location of the ecosystem change. [4.3.3]

The capacity of many species to respond to climate change will continue to be constrained by non-climate factors (*high confidence*), including but not limited to the simultaneous presence of land-use changes, habitat fragmentation and loss, competition with alien species, exposure to novel pests and diseases, nitrogen loading, and increasing carbon dioxide and tropospheric ozone. [Figure 4-1, 4.2.4, 4.3.3]

A changing climate exacerbates other threats to biodiversity (*high confidence*). In some systems, such as high altitude and latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function. Since the specific changes in individual regions depend on the nature of the projected regional climate change, the confidence in specific future

ecosystem changes is limited by the confidence assigned to regional climate change projections by Working Group I. [4.3.2, 4.3.3, 4.4.1]

Terrestrial plant and animal species will continue to move their ranges, alter their abundance, and shift their seasonal activities in response to projected future climate change (*high confidence*). *High confidence* in past responses, coupled with projections from a diversity of models and studies, provides *high confidence* that such responses will be the norm with continued warming. These shifts in species ranges will cause large changes in local abundance under all climate change scenarios: abundance declining in areas where climate becomes unfavorable and potentially increasing in areas where climate becomes more favorable. Such changes in species abundance lead to changes in community composition and ecosystem function. [4.2.1, 4.2.2, 4.3.2, 4.3.3]

Climate change is increasing the likelihood of the establishment, growth, spread, and survival of some invasive alien species populations in some regions (*high confidence*). Invasive species are more likely than native species to have traits that favor their survival and reproduction under changing climates. Species movement into areas where they were not present historically will be driven both by climate change and by increased dispersal opportunities associated with human activities. [4.2.4]

Even for mid-range rates of climate change (i.e., RCP 4.5 and 6.0 scenarios) many species will be unable to move fast enough to track suitable climates (*medium confidence*). See Figure TS.8. Over the last several decades many, but not all, species have tracked changes in climate. Populations of species that cannot track future climate change by migrating will find themselves in unfavorable climates and are unable to expand into newly climatically suitable areas. Species in large flat areas are particularly vulnerable because they must migrate over longer distances to keep up with climate change than will species in mountainous regions. Species with low migration capacity will also be especially vulnerable: examples include most trees, many plants, and some small mammals. Combinations of low migration capacity and large flat areas are projected to pose the most serious problems for tracking climate; for example, even the maximum observed and modeled migration rates for mid- and late-successional tree species will be insufficient to track climate change in flat areas even at moderate rates of climate change (*medium confidence*). Barriers to migration such as mountain ranges, dams, habitat fragmentation, and occupation of habitat by competing species substantially reduce the ability of species to migrate to more suitable climates (*high confidence*). Outlier populations (e.g., collections in botanical gardens or parks), as well as intentional and accidental anthropogenic transport, will speed migration (*high confidence*). [4.3.2, 4.3.3]

[INSERT FIGURE TS.8 HERE
Figure TS.8: Rate of climate change (A), corresponding climate velocities (B), and rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention (C). The thin red arrows give an example of interpretation. Rates of climate change of 0.03 °C/yr correspond to ca. 1.1 km/yr global average climate velocity. When compared to rates of displacement, this would exceed rates for most plants, many primates, and some rodents. (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis; all other rates are calculated based on the average of the CMIP5 climate model ensembles for the historical period and for the future based on the four RCP emissions scenarios. The lower bound (17% of model projections are outside this bound) is given for the lowest emissions scenario and the upper bound for the highest emissions scenario. Data were smoothed using a 20-year sliding window, and rates are based on means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century are given for each RCP scenario. Colors in the background synthesize the ability of species to track climate through displacement. (B) Estimates of climate velocity were semi-quantitatively synthesized from seven studies using a diversity of analytical approaches and spatial resolutions. The three axes represent estimated climate velocities for mountainous areas (left), for global land area (center), and for regions that are flat or have high rates of climate change (right). (C) Rates of displacement for terrestrial plants, trees, mammals, birds, phytophagous insects, and freshwater mollusks. Each box represents ~95% of the estimates, and the bar is a qualitative estimate of the median. [Figure 4-6]]

Large magnitudes of climate change will negatively impact species with populations that are primarily restricted to protected areas, mountaintops, or mountain streams, even those that potentially migrate fast enough to track suitable climates (*high confidence*). Climate change is projected to either create unsuitable climates for species that remain in these areas, or force species out of protected areas and off mountaintops. These effects are foreseen to be modest for low magnitudes of climate change (e.g., RCP 2.6) and very high for the highest

magnitudes of projected climate change (e.g., RCP 8.5). Species have already started to migrate out of protected areas and towards mountaintops over the last several decades due to a warming climate. [4.3.2, 4.3.4]

Projected climate changes imply increased extinction risk for a substantial fraction of species during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, over-exploitation, and invasive species (*very high confidence*). Uncertainties in regional climate projections, highly variable estimates from comparisons of paleontological extinctions in response to past climate changes, different methods of estimating present and future extinction risk, and the variable adaptive capacity of wild species all contribute to an extremely broad range of estimates of future extinction risk due to climate change. There is *low confidence* that global extinction risks due to climate change can be accurately quantified. There is, however, a strong consensus that current climate change pressures and their interactions with other global changes will increase extinction risk for many terrestrial and freshwater species. [4.3.2]

It is *virtually certain* that the carbon stored in land and freshwater ecosystems in the form of plant biomass and soil organic matter has increased over the past two decades in what is known as the terrestrial carbon sink. There is *low confidence* that the transfer of carbon dioxide from the atmosphere to the land will continue at a similar rate for the remainder of the century. The terrestrial carbon sink is offset to a large degree by carbon released to the atmosphere through forest conversion to farm and grazing land and through forest degradation (*high confidence*). The carbon stored thus far in terrestrial ecosystems is vulnerable to loss back to the atmosphere as a result of climate change (including indirect effects such as increased risk of fires and pest outbreaks) and land-use change (*medium confidence*). Terrestrial and freshwater ecosystems have been responsible for the uptake of about a quarter of all anthropogenic CO_2 emissions in the past half century. The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability. As a result there is *low confidence* in the ability to determine whether the net fluxes into or out of terrestrial ecosystems at the global scale have increased or decreased over the past two decades. The factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, and recovery from past disturbances (*high confidence*), but there is *low confidence* in the relative contribution by each of these and other factors. Experiments and modeling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate. Other factors associated with global change, including high temperatures, rising ozone concentrations, and in some places drought, decrease plant productivity by comparable amounts (*medium confidence*). Models provide *high confidence* that nitrogen availability will limit the response of many natural ecosystems to rising CO_2. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP 8.5 for late in the century, and none of these includes the effects of other potential confounding factors. [4.2.2, 4.2.4, 4.3.2, 4.3.3, Box 4-4]

Recent experimental, observational, and modeling studies provide *medium confidence* that forests may be more sensitive to future climate change than reported in the IPCC AR4, and that tree mortality and forest dieback could become a problem in many regions much sooner than previously anticipated. Future climate change impacts on tree mortality and tree ranges could be large (*high confidence*), but experimental, observational, and modeling studies also indicate that there is *low confidence* associated with model-based projections of the details of these impacts. As such, projections of increased tree growth and enhanced forest carbon sequestration mediated by increasing growing season length, rising CO_2 concentrations, and atmospheric nitrogen deposition are being viewed with increasingly greater caution due to the counter-balancing effects of mortality and dieback. The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products depending on the balance of the positive vs. negative effects of global change. [4.3.3, 4.3.4]

Terrestrial and freshwater ecosystems can, when pushed by climate change, cross "tipping points" and abruptly change in composition, structure, and function (*high confidence*). The crossing of these tipping points will result in significant increases in carbon emissions to the atmosphere (*medium confidence*). This has happened many times in Earth history. There are plausible mechanisms, supported by experimental evidence and model results, for the existence of ecosystem tipping points in both boreal-arctic systems and the rainforests of the Amazon basin; others may exist. Continued climate change could push the boreal-arctic system across such a tipping point in this century, and cause an abrupt transformation of the ecology and albedo of this region, as well as the release of greenhouse gases from the thawing permafrost and burning forests (*low confidence*). Adaption measures will be unable to prevent substantial change in the boreal-arctic system (*high confidence*). Continued climate change together with land use change and fire activity could also cause much of the Amazon forest to transform abruptly to

more open, dry-adapted ecosystems, and in doing so, put a large stock of biodiversity at elevated risk and create a large new net greenhouse gas source to the atmosphere (*low confidence*). The combination of climate change and land-use change in the Amazon will cause accelerated drying and drought frequency in the region (*medium confidence*), and there is *low confidence* that these Amazon changes will affect rainfall in agricultural regions elsewhere on the planet. Rigorously applied adaptation measures could lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*). Policy and market-driven interventions have caused a steep decline in deforestation in the Amazon since 2005 that has decreased anthropogenic carbon emissions to the atmosphere by 1.5% (*very high confidence*). [4.2.2, 4.2.4, 4.3.3, Box 4-3, Box 4-4, Figure 4-10]

Management actions can reduce, but not eliminate, exposure to climate-driven ecosystem impacts, and can increase ecosystem adaptability (*high confidence*). The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species this is insufficient to cope without substantial loss of species and ecosystem services, given the rate and magnitude of climate change projected under medium-range warming (e.g., RCP 6.0) or high–range warming scenarios (e.g., RCP 8.5) (*medium confidence*). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. [4.4.1, 4.4.3]

Specific regional examples include:

- In Europe, climate change will cause changes in habitats and species, with local extinction (*high confidence*) and continental scale shifts (*low/medium confidence*). The habitat of alpine plants will be significantly reduced (*high confidence*). Phenological mismatch will constrain both terrestrial and marine ecosystem functioning under climate change (*high confidence*), with a reduction in some ecosystem services (*low confidence*). The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe will increase with climate change (*medium confidence*). Biodiversity is affected in unprotected areas more than in protected areas, but Natura 2000 areas retain climate suitability for species no better and sometimes less effectively than unprotected areas (*low confidence*). All ecosystem services, particularly provisioning, regulating, and cultural services, will be degraded by climate change in at least one European sub-region. [23.6.4, 23.6.5, 23.10, Table 23.2]
- In Europe, climate change will increase damage to forests from pests and diseases in all sub-regions (*high confidence*), from wildfires in Southern Europe (*high confidence*), and from storms (*low confidence*). Climate change will cause ecological and socio-economic damages from shifts in forest tree species range, with a general trend of south-west to north-east (*medium confidence*), and in pest species distributions (*low confidence*). Short-term and long-term strategies in forest management may be an adequate measure to enhance ecosystem resistance and resilience (*medium confidence*). [23.4.4]
- In Asia, terrestrial systems are under increasing pressure from both climatic and non-climatic drivers. The projected changes in climate will impact vegetation and increase permafrost degradation during the 21st Century (*high confidence*). The largest changes are expected in cold northern and high-altitude areas, where boreal and subalpine trees will *likely* invade treeless arctic and alpine vegetation, and evergreen conifers will *likely* invade deciduous larch forest. Large changes may also occur in arid and semi-arid areas, but uncertainties in precipitation projections make these difficult to predict. Vegetation change in the more densely populated parts of Asia will be constrained by the impact of vegetation fragmentation on seed dispersal. The impacts of projected climate changes on the vegetation of the lowland tropics are currently poorly understood. Trends in phenological timing consistent with the impacts of regional warming are widespread in eastern Asia, particularly for plants. Permafrost degradation will spread during the 21st century from the southern and low-altitude margins, advancing northwards and upwards. Many models agree on the direction of change, but rates of change vary greatly between different projections. [24.2.2, 24.4.2, 24.4.3, 24.9.3]
- In Australia, loss of montane ecosystems and some endemic species, driven by rising temperatures, increased fire risk, and drying trends, can be delayed but now appears very difficult to avoid entirely, even with combined globally effective mitigation and planned adaptation (*high confidence*). Fragmentation of landscapes, limited dispersal, and evolutionary capacity limit adaptation options. Many endemic species will suffer from range contractions, and some may face local or even global extinction. [25.6.1]

- In Australasia, projected changes in climate and increasing atmospheric CO_2 have the potential to benefit forest growth in cooler regions except where soil nutrients or rainfall are limiting (*high confidence*). Spring pasture growth in cooler regions would also increase and be beneficial for animal production if it can be utilized. [25.7.1, 25.7.2]
- In North America, a global increase of 2°C would have widespread adverse impacts on many ecosystems, *likely* reducing biodiversity and ecosystem services (*high confidence*). [26.4]
- In Antarctica, warming in combination with increased water availability is expected to lead to increased productivity and biomass, and the development of community complexity in native terrestrial biota (*high confidence*). However, these responses are potentially confounded by multiple stressors, including human activities (research stations, tourism, etc.). Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous taxa, the majority expected to arrive through direct human assistance, which poses the greatest threat to terrestrial plant and animal communities in the future (*high confidence*). [28.3.3]

Coastal systems and low-lying areas

Coastal systems and low-lying areas will increasingly experience adverse impacts associated with submergence and extreme sea level flooding due to relative sea level rise (*high confidence*). Large spatial variations in the projected sea level rise, together with local factors such as subsidence, suggest that relative sea level rise can be considerably larger than projected global mean sea level rise and therefore is an important consideration in impact assessments (*very high confidence*). Changes in storms and associated storm surges may further contribute to changes in sea level extremes, but the small number of regional storm surge studies, limited spatial coverage, and different modeling approaches used means that there is *low confidence* in projections of storm surge. [5.3.1, 5.3.3]

Acidification and warming of coastal waters will continue with significant consequences for coastal ecosystems (***high confidence***). The increase in acidity will be higher in areas where eutrophication is an issue, with negative consequences for many calcifying organisms. The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*). Some warm water corals and their reefs will continue to respond to warming with species replacement, bleaching from loss of associated algae, and a decreased coral cover resulting in habitat loss. Warming will cause a decline of vegetated coastal habitats across the temperate zone. Temperate seagrass and kelp ecosystems will decline with increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*).The decline of seagrass and kelp habitats will affect food webs, biodiversity, and biogeochemical cycling in these ecosystems (*very high confidence*). The projected degradation of some marine ecosystems such as coral reefs and Mediterranean intertidal communities is *very likely* to pose substantial challenges for coastal societies where livelihoods and food security may depend on ecosystem health. In the absence of adaptation, beaches, sand dunes, and cliffs currently eroding will continue to do so under increasing sea levels (*high confidence*). Increased human-induced drivers have been the primary drivers of change in coastal aquifers, lagoons, estuaries, deltas, and wetlands (*very high confidence*). Climate-change-related drivers will exacerbate currently existing problems in these natural systems. [5.4.2, 6.2, 6.3.2, 6.3.5, 6.5.2, 30.4, 30.5.3, 30.5.6, Box CC-CR, Box CC-OA]

The population and assets exposed to coastal risk as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, urbanization, and coastward migration of people (*high confidence*). Under medium population projections, the population exposed to the 1 in 100 year coastal flood is expected to increase from 271 million in 2010 to 345 million in 2050 due to socio-economic development only. This increase in coastal population is expected to further exacerbate human pressures on coastal systems resulting from excess nutrient input, reduced run-off, and sediment delivery. [5.3.4]

The costs of inaction are larger than the sum of adaptation and residual damage costs for the 21st century at the global scale (*high agreement*). Without adaptation, hundreds of millions of people will be affected by coastal flooding and be displaced due to land loss through submergence and erosion by 2100; the majority of those affected are from East, Southeast, and South Asia (*high confidence*). Even with global mean sea-level rise of 1.3m by 2100, protection is considered economically rational for most developed coastlines in most countries (*high agreement*).

Under medium socio-economic development assumptions, the expected direct global annual cost of coastal flooding (adaptation and residual damage costs) may reach 300 US$ billion per year in 2100 without adaptation and 90 US$ billion per year with adaptation under a 1.26 m sea-level rise scenario. [5.4.3, 5.5.3]

The impacts of climate change on coasts and the required level of adaptation vary strongly between regions and countries (*high confidence*). While developed countries are expected to be able to adapt to even high levels of sea-level rise, small island states and some low-lying developing countries are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of GDP (*high agreement*). Developing countries and small island states within the tropics relying on coastal tourism are impacted not only directly by future sea-level rise and associated extremes but also by the impacts of coral bleaching and ocean acidification and reductions in tourist flows from other-regions **(***very high confidence*). [5.4.3, 5.5.3]

Specific regional examples include:

- In Africa, the impacts of climate change, mainly through sea level rise, combined with other extreme events (such as high tide levels and high storm swells) have the potential to threaten coastal zones, particularly coastal towns (*high confidence*). The example of the Kwa Zulu Natal coast (South Africa), where Durban is located, which was affected by a combination of high water level and high storm swell in March 2007, is indicative of what could happen. There is growing evidence that the costs of these impacts will increase for economic sectors and people living in these zones (*medium confidence*). [22.3.2, 22.3.7]
- In Africa, ocean ecosystems, in particular coral reefs, will be affected by climate-change-induced ocean acidification. Ocean ecosystems are also affected by changes in upwelling, with ramifications for crucial economic activities, mainly fisheries (*medium confidence*). [22.3.2, 22.3.4]
- In Europe, the costs of adapting dwellings or upgrading coast defence will increase under all scenarios (*high confidence*). Climate change will entail the loss or movement of coastal wetlands. [23.3.2, 23.6.5, 23.7.6]
- In Asia, coastal and marine systems are under increasing pressure from both climatic and non-climatic drivers (*high confidence*). Mean sea level rise will *very likely* contribute to upward trends in extreme coastal high water levels, and in the Asian Arctic, rising sea levels will interact with projected changes in permafrost and the length of the ice-free season to cause increased rates of coastal erosion (*high agreement, medium evidence*). Coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea levels. Widespread damage to coral reefs correlated with episodes of high sea-surface temperature has been reported in recent decades, and such damage will increase during the 21st century as a result of both warming and ocean acidification (*high confidence*). [24.4.3]
- In Australia, significant change in community structure of coral reef systems, driven by increasing sea-surface temperatures and ocean acidification, can be delayed but now appears very difficult to avoid entirely, even with combined globally effective mitigation and planned adaptation (*high confidence*). The natural ability of reefs to adapt to projected changes is limited. [Box CC-CR, 25.6.2, 30.5]
- In Australia and New Zealand, rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure, and housing (*high confidence*). Widespread damages to coastal infrastructure and low-lying ecosystems would present major challenges if sea level rise exceeds 1m. Managed retreat is a long-term adaptation strategy for human systems, but options for some natural ecosystems are limited due to the rapidity of change and lack of suitable space for inland migration. Risks from sea level rise are *very likely* continue to increase beyond 2100 even if temperatures are stabilized. [WGI AR5 13.ES, Box 25-1, Table 25-1, 25.4.2, 25.6.1-2]
- In Brazil, fisheries' co-management—a participatory process involving local fishermen communities, government, academia, and NGOs—favors a balance between conservation of marine fisheries, coral reefs, and mangroves, and the improvement of livelihoods, as well as the cultural survival of traditional populations. [27.3.3]
- In the Arctic, the primary conservation concern for polar bears over the foreseeable future is the recent and projected loss of annual ice over continental shelves and decreased ice duration and thickness (*high confidence*). [28.2.2]

Marine systems

Physical effects of climate change on marine ecosystems may act, under some circumstances, as an additional pressure that cannot be ameliorated by local conservation measures or a reduction in human activities like fishing (*high confidence*). Effects of climate change will thus complicate management regimes, e.g. presenting direct challenges to the objectives of spatial management once species undergo large-scale distributional shifts. This increases the vulnerabilities of marine ecosystems and fisheries. [6.4]

Ocean acidification resulting from the increased flux of atmospheric CO_2 into the ocean represents a fundamental challenge to marine organisms and ecosystems, although the extent of its influence varies with the taxa and process involved (*high confidence*). Evidence from controlled laboratory experiments and mesocosm studies indicate that ocean acidification significantly impacts a large range of organisms (e.g., corals, fish, pteropods, coccolithophores, and macroalgae), physiological (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function), and ecosystem processes (e.g., productivity, reef building, and erosion), but there are fewer field studies that have shown (or not shown) direct ecosystem changes. Ocean acidification and its effects are characterized in Box TS.9. [30.3.1, 30.3.2, 30.4, Box CC-OA, 6.2, 6.3, 6.5, Box 5-1, Box 6-2]

Several environmental drivers act simultaneously on ocean biota, often leading to interactive effects and complex responses (*high confidence*). Ocean acidification and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms such as corals, coralline algae, molluscs, crustaceans, and fishes. Genetic adaptation may occur; the capacity to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). [6.2, 6.3.2, 6.3.5, 6.5.2, 30.4, 30.5.3, 30.5.6, Box CC-CR]

The oceans currently provide about half of global net primary production (NPP). Environmental controls on NPP include temperature, CO_2, nutrient supply, and irradiance, all of which are projected to be altered (WGI AR5). The direction, magnitude, and regional differences of a change of NPP in the open ocean as well as in coastal waters have *limited evidence* and *low agreement* for a global decrease projected by 2100. At high (polar) latitude an increase in NPP is also projected with *low confidence*. [6.3.1, 6.5.1]

Modeling projects that, through species gains and losses in response to warming, the diversity of marine animals and plants will increase at mid and high latitudes (*high confidence*) and fall at tropical latitudes (*low confidence*), leading to a large-scale redistribution of global catch potential for fishes and invertebrates (*medium confidence*). If a decrease in global ocean net primary production or a shift downwards in the size spectrum of primary producers occurs, the overall fisheries catch potential will decrease. Animal displacements are projected to lead to a 30–70% increase in the fisheries yield of high-latitude regions but a drop of 40–60% in the tropics by 2055 relative to 2005 under the SRES A1B scenario (*medium confidence* for the general trend of shifting fisheries yields, *low confidence* for the magnitude of change). See Figure TS.9. Climate change impacts on the abundance and distribution of harvested aquatic species, both freshwater and marine, and aquaculture production systems in different parts of the world, are expected to continue with negative impacts on nutrition and food security for especially vulnerable people in some regions but with benefits in other regions that become more favorable for aquatic food production (*high agreement, medium evidence*). [6.2.5, 6.3.2, 6.4, 6.5, 6.5.2, 7.2.1, 7.3.2, 7.4.2, 7.5.1]

[INSERT FIGURE TS.9 HERE
Figure TS.9: A) Multi-model mean changes of projected vertically-integrated net primary production (small and large phytoplankton). To indicate consistency in the sign of change, regions are stippled where all models (four in total) agree on the sign of change. Changes are annual means under the SRES A2 scenario (between RCP 6.0 and 8.5) for the period 2080 to 2099 relative to 1870 to 1889. B) A projection of maximum fisheries catch potential of 1000 species of exploited fishes and invertebrates from 2000 to 2050 under the SRES A1B scenario. C) Example of changes occurring within fisheries across the ocean. [Figures 6-14, 6-15, and 30-15]]

The observed and projected impacts on ocean ecosystems and processes reveal significant regional differences that will benefit from differing policy responses and adaptation approaches (*medium agreement, medium evidence*). Changing distribution and abundance of fish species as waters warm and acidify suggest the need for flexible and informed decision-making. For example, tuna, a key fisheries species, are highly sensitive to changes in sea temperature, and changes in their distribution and abundance will provoke new technological and policy

challenges. The cross-boundary migration of fish stocks (from the waters of one nation to another) will benefit from international cooperation and evidence-based decision making. [30.5.5, 30.6.3]

Building dynamic fisheries management and sustainable aquaculture represent opportunities for adaptation to changes in the distribution and productivity of fish stocks (*high agreement, medium evidence*). The application of ecosystem-based management that includes climate change to manage the development and maintenance of fish stocks represents a key tool for adapting to changes resulting from climate change. Reducing non-sustainable fishing (e.g., bottom trawling, "ghost" fishing) provides an avenue for adapting to climate impacts by reducing the impact of additional stressors. Changes to coastal fishing due to the loss of coastal ecosystems will require adaptation strategies such as marine protected areas, alternative livelihoods, and/or the movement of people and industry sectors. Key adaptations for fisheries are for policy and management to maintain ecosystems in a state that is resilient to change, to enable occupational flexibility, and to develop early warning systems for extreme events (*high agreement, medium evidence*). Industries such as nature-based tourism will require similar strategies for decision-making. [30.6.3, 6.5, 7.5.1]

Projected change to ocean ecosystems as a result of ocean warming and acidification will reduce access to food, and increase poverty and disease in many countries (*medium agreement, limited evidence*). Reduced access to food in some coastal regions as a result of declining fisheries will affect an increasing number of already vulnerable people and will result in associated health impacts. [30.6.3, 30.6.5, 6.4]

Climate change, by increasing temperatures and altering surface winds, has influenced ocean mixing, nutrient levels, and primary productivity. These changes are *very likely* to have positive consequences for some fisheries and negative ones for others through the de-oxygenation of deep water environments and associated spread of hypoxic zones (*medium agreement, medium evidence*). In regions where primary production has increased (or is predicted to increase), such as in the High Latitude Spring Bloom Systems, Eastern Boundary Upwelling Ecosystems, and Equatorial Upwelling, energy transfer to higher trophic levels is *likely* to increase along with microbial activity. Increased primary productivity is *likely* to lead to an increased transfer of organic carbon to deep sea habitats stimulating respiration and drawing down oxygen levels in some areas. These changes are further influenced by the contribution of nutrients from coastal pollution, leading to the expansion of hypoxic (low in oxygen) zones in areas such as the Gulf of Mexico, North Sea, Arabian Sea, and coastal areas of many countries. Increasing temperatures will also reduce the solubility of oxygen, adding to oxygen stress (*very high confidence*). [30.5.2, 30.5.4, 30.5.6, 6.2, 6.3, 6.5]

Changes to surface winds, sea level, wave height, and storm intensity will increase the risks associated with coastal and ocean based industries such as shipping, oil, gas, and mineral extraction (*medium agreement, medium evidence*). Storm impacts on coastal areas will increase with sea level rise through greater storm surge impacts. [WGI AR5 3.7.4] Strategies will require consideration of these changes in the design and use of ocean-based infrastructure together with the evolution of policy for reducing risks to equipment and people. New opportunities for shipping, oil, gas, and mineral extraction, as well as international issues over access and vulnerability, are expected to evolve as waters warm, particular in high latitude regions. [30.6, 6.5]

Ocean ecosystems and associated sub-regions offer a large potential for carbon dioxide mitigation strategies (*medium agreement, limited evidence*). Ecosystems such as mangroves, seagrass, and salt marsh represent potentially significant carbon sequestration strategies (e.g., "blue carbon"). Reducing highly anoxic habitats through coastal restoration (and hence the emission of methane) also represents significant mitigation opportunities, although an understanding of these opportunities is limited. Sequestration of anthropogenic CO_2 into deep ocean areas has been explored, although studies indicate significant hurdles with respect to expense and to the vulnerability of deep water marine ecosystems. [30.7]

Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (e.g., purposeful nutrient fertilization, binding of CO_2 by enhanced alkalinity, and direct CO_2 injection into the deep ocean) have very large associated environmental footprints (*high confidence*), with some requiring purposeful alteration of ocean ecosystems for implementation. Alternative methods focusing on solar radiation management leave ocean acidification unabated. [6.4.2]

Specific regional examples include:

- In Europe, climate change will not decrease net fisheries economic turnover in some parts of Europe (e.g. Bay of Biscay) (*low confidence*) due to introduction of new (high temperature tolerant) species. Climate change will not entail relocation of fishing fleets (*high confidence*). High temperatures will increase frequency of harmful algal blooms (*medium confidence*). [23.4.6]
- In the polar regions, shifts in the timing of seasonal biomass production could disrupt matched phenologies in food webs, leading to decreased abundance of high latitude marine organisms (*medium confidence*). Ocean acidification has the potential to inhibit egg development and shell formation of some zooplankton and krill with potentially far-reaching consequences to food webs. Loss of sea ice in summer is expected to enhance secondary pelagic production in the Arctic with associated changes in the energy pathways within the marine ecosystem. [28.2.2, 28.3.2]

Food production systems and food security

Without adaptation, moderate warming of up to 2°C local temperatures is expected to reduce yields on average for the major cereals (wheat, rice, and maize) in temperate regions, although many individual locations may benefit (*medium confidence*). There is confirmation that even modest warming up to 2°C will decrease yields in low-latitude tropical regions (*medium agreement, robust evidence*). Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. From the 2070s onwards, all of the positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are *very likely* by this time and substantial, particularly for wheat (*high agreement, robust evidence*). [7.4, Figures 7-5, 7-6, and 7-7]

Changes in climate and CO_2 levels will enhance the distribution and increase the competiveness of agronomically important and invasive weeds (*high agreement, robust evidence*). Rising CO_2 reduces the effectiveness of herbicides (*high agreement, medium evidence*). The effects of climate change on disease pressure on food crops is uncertain, with evidence pointing to changed geographical ranges of diseases but less certain changes in disease intensity (*low agreement, medium evidence*). [7.3.2]

Impacts of increased heat stress and more frequent extreme events will be negative in all regions for livestock (*high agreement, robust evidence*). Changes in animal diseases and vectors are less certain (*medium agreement, medium evidence*). Livestock systems' adaptations center around adjusting management to the available resources, using breeds better adapted to the prevailing climate, and removing barriers to adaptation such as improving credit access (*medium evidence, medium agreement*). [7.3.2, 7.5]

Adaptation possibilities of food systems to climate change show a very wide range in effectiveness, with *medium confidence* that adaptation will increase in effectiveness with increasing local mean temperature up to ca. 3°C local warming above pre-industrial, after which the net benefits no longer increase (*medium agreement, medium evidence*). Most studies, however, have focused on food production rather than on adapting food systems. Generally, adaptation leads to lower reductions in food production than in its absence with an overall crop yield difference in adaptation cases of about 15-20% over non-adaptation cases (*high agreement, medium evidence*), with more effective adaptation at higher latitudes (*medium agreement, limited evidence*), but with some adaptation options more effective than others. Thus, benefits of adaptation are greater for wheat, rice, and maize in temperate rather than tropical regions (see Figure TS.10). A range of potential adaptation options exists across all food system activities, not just in food production, but benefits from potential innovations in food processing, packaging, transport, storage, and trade are insufficiently researched. [7.1, 7.3.2, 7.5, 7.6, Figure 7-5, Figure 7-9] Urban food-adaptation is linked to progressive public policy on food security and livelihood development, addressing constraints in agricultural production and food supply chains, and limiting the impact of food price shocks caused by extreme events on the food and nutrition security of the poor. [8.3]

[INSERT FIGURE TS.10 HERE
Figure TS.10: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colors denote percentage change in crop yield. Data are plotted according to the 20-year period in which the center point of the projection period falls. [Figure 7-6]]

Specific regional examples include:

- In Africa, recent evidence further strengthens a key finding from the AR4 that "agricultural production and food security (including access to food) in many African countries and regions are *likely* to be severely compromised by climate change and climate variability" (*high confidence*). Temperature rise and a reduction in growing season length by mid-century are expected to significantly reduce crop productivity with strong adverse effects on food security. New evidence is also emerging that fisheries and high-value perennial crops could also be adversely affected by temperature rise, and that the pressure of pest and diseases on crops and livestock is expected to increase as a result of climate change and other factors. Moreover, new challenges to food security are emerging as a result of strong urbanization trends on the continent and increasingly globalized food chains, which require better understanding of the multi-stressor context of food and livelihood security in Africa. [22.3.4]
- In Europe, climate change will increase yields in Northern Europe (*medium confidence*) but decrease cereal yields in Southern Europe (*high confidence*). Compared to AR4, new evidence regarding future yields in Northern Europe is less consistent regarding the magnitude and sign of change. In Northern Europe, climate change will increase the seasonal activity of pests and plant diseases (*high confidence*). Climate change will adversely affect dairy production in Southern Europe because of heat stress in lactating cows (*medium confidence*). Climate warming has caused the spread of blue tongue disease in ruminants in Europe (*high confidence*) and northward expansion of tick vectors (*medium confidence*). [23.4.1, 23.4.2, 23.5.1]
- In Europe, climate change will increase irrigation needs (*high confidence*), but future irrigation will be constrained by reduced runoff, demand from other sectors, and economic costs. By 2050s, irrigation will not be sufficient to prevent damage from heat waves to crops (*medium confidence*). System costs will increase under all climate scenarios (*high confidence*). Integrated management of water can address future competing demands among agriculture, conservation, and human settlements. [23.4.1, 23.4.3, 23.7.2]
- In Europe, shifts in agriculture production across sub-regions will occur (*medium confidence*). Climate change will alter the productivity of bioenergy crops by shifting their distribution northward (*high confidence*). Elevated atmospheric CO_2 can improve drought tolerance of bioenergy crop species due to improved plant water use, maintaining high yields in future climate scenarios (*medium confidence*). [23.4.5] Climate change will change the geographic distribution of wine grape varieties (*high confidence*). This will reduce the economic value of wine products and the livelihoods of local wine communities in Southern and Continental Europe (*medium/low confidence*). Some adaptation is possible through technologies and good practice. [23.3.5, 23.4.1, 23.4.5, 23.5.4, Box 23-1]
- In Asia, the impacts of climate change on food production and food security will vary by region with many regions experiencing a decline in productivity (*medium confidence*). This is evident in the case of rice production. Most models using a range of GCMs and SRES scenarios show that higher temperatures will lead to lower rice yields as a result of shorter growing periods and heat-induced sterility. There are a number of regions that are already near the critical temperature threshold. However, CO_2 fertilization may at least in part offset yield losses in rice and other crops. In Central Asia, some areas could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters, and slight increase in winter precipitation), while others could be losers (western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase water demands for irrigation, and exacerbate desertification). In the Indo-Gangetic Plains of South Asia, there could be up to 50% decrease in the most favorable and high yielding wheat area due to heat stress at 2x CO_2. There are many potential adaptation strategies such as crop breeding, but research on their effectiveness is limited. [24.4.4]
- In Australia and New Zealand, rainfall changes and rising temperatures will shift agricultural production zones (*high confidence*). Significant reduction in food production in the Murray-Darling Basin, far south-eastern Australia, and some eastern and northern areas of New Zealand would present major challenges if scenarios of severe drying are realized. More efficient water use, allocation, and trading would increase the resilience of systems in the near term but cannot prevent significant reductions in agricultural production and severe consequences for ecosystems and some rural communities at the dry end of the projected range. [25.2, 25.5.1, 25.7.2, Box 25-5]
- In North America, without adaptation, projected changes in temperature, precipitation, and extreme events would result in notable productivity declines in major crops by the end of the 21st Century (*very high confidence*). Given that North America is a significant source of global food supplies, there will *likely* be a

negative effect on global food security if projected productivity declines are not addressed with substantial investments in adaptation (*medium confidence*). Adaptation may ameliorate many climate impacts to North American agriculture, but the institutional support mechanisms currently in place are insufficient to ensure effective, equitable, and sustainable adaptation strategies. [26.5]

- In Central and South America, changes in agricultural productivity in response to climate change are expected to have a great spatial variability. In Southeastern South America, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (SRES: A2, B2) (*medium confidence*). In Central America, northeast of Brazil, and parts of the Andean region, increases in temperature and decreases in rainfall could decrease the productivity in the short-term (before 2025), threatening the food security of the poorest population (*medium confidence*). The great challenge for Central and South America will be to increase food and bioenergy production and at the same time sustain environmental quality in a scenario of climate change. [27.3.4]
- In the Arctic, significant impacts on the availability of key subsistence marine and terrestrial species are projected as climate continues to change with the ability to maintain economic livelihoods being affected (*high confidence*). Changing sea-ice conditions will result in more difficult access for hunting marine mammals. [28.2.6]

Urban areas

Increasing concentration of populations, assets, and economic activities in the urban areas of almost all countries, irrespective of income level, will increase the concentration of climate-related risks for a large and growing proportion of the world's population (*medium confidence*, based on *high agreement, medium evidence*). This could threaten economic and development processes, poverty reduction, and ecological sustainability. Furthermore, projections for the next few decades suggest that it is in and around urban areas that almost all the increase in the world's population and much of the increment in capital formation, economic activity, infrastructure development, ecosystem degradation, and emissions will take place. [8.1, 8.3, 8.4]

Adapting urban centers' economic base can enhance comparative advantage, deepen climate resilience, and limit disadvantage (*high agreement, medium evidence*). Climate change will shift the comparative advantages of cities and regions and differentially threaten or enhance the resource, asset, and economic base and so lead to significant structural changes and impacts on local, national, and potentially the global economy. Effective adaptation can protect a city's economic base via a mix of strategies. These include extreme weather exposure reduction via effective land-use planning, selective relocation and structural measures, reduction in the vulnerability of lifeline infrastructure and services, and measures to assist vulnerable sectors and households, mitigation of business interruption and capital stock losses, and support to the "waste economy" and the "green economy." These adaptation actions may be easier and cheaper to implement in new and peri-urban development. [8.3]

Good quality, affordable, and well-located housing provides one of the bases for city-wide adaptation (*high confidence*), by conforming to appropriate health and safety and climate-resilient building standards and having sufficient residual structural integrity over its service life to protect its occupants against extreme weather, especially heat waves and storms. It is particularly important for vulnerable groups, especially children and older residents with chronic health conditions. This can be enabled via a range of structural interventions, interventions that reduce risks to housing and support access to quality housing for low-income groups, non-structural interventions (like insurance), and disaster risk reduction measures. Well-coordinated strategies are required to address a multiplicity of agencies working at various levels, overlapping regulations, and lack of committed resources. [8.3]

Rural areas

Future impacts of climate change on the rural economic base and livelihoods, land-use, and regional interconnections are at the latter stages of complex causal chains (*high confidence*). These flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. This increases the uncertainty associated with any particular projected impact. [9.3.3]

Major impacts of climate change in rural areas will be felt through impacts on water supply, food security, and agricultural incomes (*high confidence*). In certain countries shifts in agricultural production, of food and non-food crops, could take place. Areas suitable for cultivation of coffee, tea and cocoa, which support millions of smallholders in over 60 countries, will be significantly reduced. Price rises, which may be induced by extreme weather events apart from other factors, have a disproportionate impact on the welfare of the poor in rural areas, such as female-headed households and those with limited access to modern agricultural inputs, infrastructure, and education. Adaptation can build on current responses to climate variability, in production of food crops, cash crops and livestock and in water management, but these may not be sufficient to deal with the range of projected climate change. [9.3.3, 9.3.4, 9.4.1, 9.4.3]

Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security while affecting rural households depending on whether they are net buyers or net sellers of food (*medium* to *high confidence*). Deepening agricultural markets through reforming trade and making institutional efforts to improve the predictability and the reliability of the world trading system, as well as by investing in additional supply capacity of small-scale farms in developing countries, could help reduce market volatility and manage food supply shortages that might be caused by climate change (*medium agreement*). [9.3.3]

Most studies on valuation highlight that climate change impacts will be significant especially for the developing regions, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*high confidence*). Valuation of climate impacts needs to draw upon both monetary and non-monetary indicators. The valuation of non-marketed ecosystem services and the limitations of economic valuation models which aggregate across multiple contexts pose challenges for valuing impacts in rural areas. [9.3.4]

Specific regional examples include:

- In parts of Asia, increases in flood and drought will exacerbate rural poverty due to negative impacts on rice crops and increases in food prices and the cost of living (*high confidence*). [24.4.6]

Key economic sectors and services

Climate change would reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*high agreement, robust evidence*). The balance of the two depends on the geographic, socioeconomic, and technological conditions. Increasing income will allow people to regulate indoor temperatures to a comfort level that leads to fast growing energy demand for air conditioning even in the absence of climate change in warm regions with low income levels at present. Energy demand will be influenced by changes in demographics (upwards by increasing population and decreasing average household size), lifestyles (upwards by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices, and the abundance and energy efficiency of other electric household appliances. The relative importance of these drivers varies across regions and will change over time. [10.2]

Climate change would affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling), or the locations (coastal regions, floodplains) involved (*high agreement, robust evidence*). Gradual changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) and possible changes in the frequency and intensity of extreme weather events will progressively affect operation over time. Climate-induced changes in the availability and temperature of water for cooling are the main concern for thermal and nuclear power plants, but several options are available to cope with reduced water availability. Similarly, already available or newly developed technological solutions allow firms to reduce the vulnerability of new structures and enhance the climate suitability of existing energy installations. [10.2]

Climate change would influence the integrity and reliability of pipelines and electricity grids (*medium agreement, medium evidence*). Pipelines and electric transmission lines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Climate change is *about as likely as not* to require the adoption of technological solutions for the construction and operation of

pipelines and power transmission and distribution lines from other geographical and climatic conditions, adjustments in existing pipelines, and improvements in the design and deployment of new ones in response to the changing climate and weather conditions. [10.2]

Climate change would negatively affect transport infrastructure (*high agreement, limited evidence*). Transport infrastructure malfunctions if the weather is outside the design range, which would happen more frequently should climate change. All transportation infrastructure is vulnerable to freeze-thaw cycles; paved roads are particularly vulnerable to temperature extremes and unpaved roads to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.4]

Climate change would affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*high agreement, robust evidence*), and tourists would be inclined to spend their holidays at higher altitudes and latitudes (*high agreement, medium evidence*). The economic implications of climate-change-induced changes in tourism demand and supply may be substantial, with gains for countries closer to the poles and higher up the mountains and losses for other countries. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically and seasonally. [10.6]

Climate change would affect the health sector (*high agreement, medium evidence*) through increases in the frequency, intensity, and extent of extreme weather events adversely affecting infrastructure and increase the demands for services due to the human health impacts of climate change, placing additional burdens on public health, disease burden, and health care personnel and supplies; these have economic consequences. [10.8]

Climate change would have impacts, heterogeneous in both sign and size, on water resources and water use (*high agreement, robust evidence*), but the economic implications are not well understood. Economic impacts include flooding, scarcity, and cross-sectoral competition. Water scarcity and competition for water, driven by institutional, economic, or social factors, may mean that water assumed to be available for a sector is not. [10.3]

The impacts of climate change would decrease productivity and economic growth, but the magnitude of this effect is not well understood (*high agreement, limited evidence*). Climate could be one of the causes why some countries are trapped in poverty, and climate change may make it harder to escape poverty traps. [10.9]

Not all key sectors have been subject to detailed research based on a comprehensive assessment across economic sectors. Few studies have evaluated the possible impacts of climate change on mining, manufacturing, or services (apart from health, insurance, and tourism). Further research, collection, and access to more detailed economic data and the advancement of analytic methods and tools will be required to further assess the potential impacts of climate on key economic systems and sectors. [10.5, 10.8, 10.10]

Specific regional examples include:

- In Europe, climate warming will decrease space heating demand and increase cooling demand (*high confidence*), with income growth driving the largest part of this increase from 2000-2050 (especially in eastern regions) (*medium confidence*). Energy efficient buildings and cooling systems as well as demand-side management will reduce future energy demands. Climate change will increase the problems associated with overheating in domestic housing. [23.3.2, 23.3.4]
- In Europe, climate change will decrease hydropower production from reductions in rainfall in all sub-regions except Scandinavia (*high confidence*). Climate change will have no impact on wind energy production before 2050 (*medium confidence*) and only a small impact after 2050 (*low confidence*). Climate change will inhibit thermal power production during summer (*medium confidence*). Plant modifications and operational changes can reduce adverse impacts. [23.3.4]
- In Europe, climate change is *likely* to further increase coastal and river flood risk and, if unabated, will substantially increase flood damages (monetary losses and people affected). Adaptation can prevent most of the projected damages (*high confidence*, based on *high agreement, medium evidence*). [23.3.1, 23.5.1, 23.7.1, 23.8.3]
- In Europe, climate change will affect the impacts of hot and cold weather extremes on transport leading to economic damage and/or adaptation costs, as well as some benefits during winter (e.g., reduction of maintenance costs) (*medium confidence*). Climate change will reduce severe accidents in road transport and adversely affect inland water transport particularly the Rhine in summer after 2050. Damages to rail

infrastructure from high temperatures will increase. Adaptation through maintenance and operational measures can reduce adverse impacts to some extent. [23.3.3]

- In Europe, no significant impacts are projected before 2050 in winter or summer tourism except for ski tourism in low altitude and mid altitude sites and under limited adaptation (*medium confidence*). After 2050, tourism activity will decrease in southern Europe (*low confidence*) and increase in northern/continental Europe (*medium confidence*). Artificial snowmaking will prolong the activity of some ski resorts (*medium confidence*). [23.3.6]
- In Europe, the capacity to adapt will be higher than for other world regions, but there are important differences in impacts and the capacity to respond within the European sub-regions. Climate change will affect economic activity in southern Europe more than other sub-regions (*medium confidence*), [Table 23.4, 23.9.1] and increase future intra-regional disparity (*low confidence*). [23.9] The Mediterranean (part of Southern region) is particularly vulnerable to climate change as multiple sectors will be adversely affected (tourism, agriculture, forestry, infrastructure, energy, population health) (*high confidence*). [23.9, 23.9.1, Box 23-3, Table 23.4]
- In Australia and New Zealand, increased frequency and intensity of flood damage to settlements and infrastructure are projected, driven by increasing extreme rainfall although the amount of change remains uncertain (*high confidence*). In many locations, continued reliance on increased protection alone would become progressively less feasible. Increased damages to ecosystems and settlements, economic losses, and risks to human life from wildfires in most of southern Australia and many parts of New Zealand are projected, driven by drying trends and rising temperatures (*high confidence*). Building codes, design standards, local planning mechanisms, and public education can assist with adaptation and are being implemented in regions that have experienced major events. These impacts have the potential to be severe but can be moderated or delayed significantly by globally effective mitigation combined with adaptation, with an increasing need for transformative adaptation for greater rates and magnitude of change. [25.2, Table 25-1, 25.4.2, 25.6.1, 25.7.1, Box 25-6, 25.10.3, Box 25-8]
- In New Zealand and southern parts of Australia, projected changes in climate have the potential to reduce energy demand for winter heating (*high confidence*). [25.7.4]
- In North America, there is an emerging concern that dislocation in one sector of the economy may have an adverse impact on other sectors due to supply chain interdependency (*medium confidence*). [26.7]
- In the Arctic, climatic and other large-scale changes can have potentially large effects on communities where relatively small and narrowly based economies leave a narrower range of adaptive choices (*high confidence*). Increased economic opportunities and challenges for culture, security, and environment are expected with the increased navigability of Arctic marine waters and the expansion of land- and fresh water-based transportation networks. Rising temperatures, leading to the further thawing of permafrost and changing precipitation patterns, have the potential to affect all infrastructure types and related services in the Arctic. [28.2.6, 28.4.2]

Human health

If climate change continues as projected in scenarios in the next few decades, the major increases of ill-health compared to no climate change will occur with *high confidence* through:

- Greater incidence of injury, disease, and death due to more intense heat waves, storms, floods, and fires.
- Increased risk of under-nutrition resulting from diminished food production in poor regions.
- Loss of work capacity and reduced labor productivity in vulnerable populations.
- Increased risks of food- and water-borne diseases and vector-borne infections.
- Modest improvements in some areas due to lower impacts of cold, shifts in food production, and reduction of disease-carrying vectors. These positive effects will be out-weighed, world-wide, by the magnitude and severity of the negative effects of climate change.

Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development, particularly among the poorest and least healthy groups. [11.4, 11.5, 11.6, 11.7]

For RCP 8.5 by 2100, most of the world land area will be experiencing annual mean temperatures at least 4°C above those of 1986-2005. This means that important limits to adaptation for health impacts may have been exceeded in many areas of the world during this century (*high confidence*). These relate to sea level rise,

storms, loss of agricultural productivity, and daily temperature/humidity conditions that exceed coping mechanisms, making potentially large areas seasonally unsuitable for normal human activities, including growing food or working outdoors. [11.8]

Climate change is expected to substantially affect regional air quality, for example near surface ozone concentrations; however, this effect also depends strongly on future emissions. [21.3.3, 21.5.3]

The most effective adaptation measures for health in the immediate term are programs that extend basic public health measures and essential health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). [11.6]

Specific regional examples include:

- In Africa, climate change is expected to increase the burden of a wider range of health outcomes (*medium confidence*). Findings on malaria are similar to AR4, emphasizing the spatial and temporal spread of malaria in the East Africa Highlands and increased transmission intensity in South Africa. Indirectly, climate change could increase the burden of malnutrition, which will have the highest toll on children and women. Adaptation in the health sector will build on existing public health interventions as well as specific adaptation measures such as early warning systems. [22.3.5, 22.4.5]
- In Europe, climate change will increase the frequency tropospheric ozone events (exceedences) in the future (*low confidence*), even assuming future emissions reductions. [23.6.1]
- In Europe, particularly in Southern Europe, climate change will increase the frequency and intensity of heat waves (*high confidence*) with adverse implications for health, agriculture, energy production, transport, tourism, labour productivity, and built environment, and heat-related deaths and injuries will increase (*medium confidence*). Climate change will change the distribution and seasonal pattern of some human infections, including those transmitted by arthropods. [23.2.2, 23.5.1, Table 23.4]
- In Asia, more frequent and intense heat-waves will increase mortality and morbidity in vulnerable groups. Increases in heavy rain and temperature will increase the risk of diarrheal diseases and malaria (*high confidence*). [24.4.6]
- In Australia, increasing morbidity, mortality, and infrastructure damages during heat waves, resulting from increased frequency and magnitude of extreme temperatures, have the potential to be severe but can be moderated or delayed significantly by globally effective mitigation combined with adaptation (*high confidence*). Vulnerable populations include the elderly, children, and those with existing chronic diseases; aging trends and prevailing social dynamics constrain effectiveness of adaptation responses, with an increasing need for transformative adaptation for greater rates and magnitude of change. [25.8.1]
- In New Zealand and southern parts of Australia, projected changes in climate have the potential to reduce morbidity from winter illnesses (*high confidence*). [25.8.1]
- In North America, the effect of increasing heat extremes on health will depend on the pace of adaptation (*high confidence*). Given current levels of adaptation, there are *likely* to be increased health impacts from heat extremes among vulnerable communities, populations, and individuals. Conditional on an increase in storm severity under a changing climate, there are *likely* to be continued human health risks in the absence of specific adaptation planning. [26.6]
- In Central and South America, climate variability and change may exacerbate current and future risks to health, given the region's vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, and pollution. [27.3.7]

Human security

Climate change threatens human security, because it a) undermines livelihoods, b) compromises culture and identity, c) increases migration that people would rather have avoided, and d) undermines the ability of states to provide the conditions necessary for human security (*high agreement, robust evidence*). Human security breakdowns almost never have single causes, but instead emerge from the interaction of multiple factors. For populations that are already socially marginalized, are resource dependent, and have limited capital assets, human security will be progressively undermined as the climate changes. Increases in the rate and magnitude of climate

change increase the risk to human security by exacerbating negative feedbacks between cultural processes, migration, and violent conflict. See Figure TS.11. [12.1.2, 12.2, 12.7]

[INSERT FIGURE TS.11 HERE
Figure TS.11: Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between elements. Examples of positive and negative changes in security associated with interventions indicated by arrows. [Figure 12-3]]

Climate change will have significant impacts on forms of migration that compromise human security (*medium agreement, medium evidence*). Some migration flows are sensitive to changes in resource availability and ecosystem services. Major extreme weather events have in the past led to significant population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. There is evidence that many vulnerable groups do not have the resources to be able to migrate to avoid the impacts of floods, storms, and droughts. There is evidence from models, scenarios, and observations that coastal inundation and loss of permafrost can lead to migration and resettlement. Migrants themselves may be vulnerable to climate change impacts in destination areas, particularly in urban centers in developing countries. [9.3.3, 12.3.2, 12.4.2]

Climate change will lead to new challenges to states and will shape both conditions of security and national security policies (*medium agreement, medium evidence*). Physical aspects of climate change, such as sea level rise, extreme events, and hydrologic disruptions, pose major challenges to vital transportation, water, and energy infrastructure. Some states are experiencing major challenges to their territorial integrity, including Arctic countries, small island states, and other states highly vulnerable to sea level rise. Some impacts of climate change, such as changes in sea ice, transboundary and shared water resources, and the migration of pelagic fish stocks, have the potential to increase rivalry among states. There is evidence that the presence of robust institutions can manage many of these rivalries such that human security is not severely eroded. These threats to national security will affect the capacity of states and communities to provide human security. [12.5.4, 12.6]

Climate change affects cultures and the cultural expressions important for maintaining identity and traditional and local forms of knowledge (*high agreement, medium evidence*). Climate change impacts will lead to significant changes in environmental and societal conditions throughout the natural world, and in human settlements. These changes will compromise dimensions of the cultural core and assets that are highly valued by societies. The magnitude of the perceived loss depends on the robustness of cultural identity and the mechanisms for maintaining and transferring knowledge. [12.3]

Specific regional examples include:

- In Europe, climate change and sea level rise will damage European cultural heritage, including buildings, local industries, landscapes, and iconic places such as Venice (*medium confidence*), and some cultural landscapes will be lost forever (*low/medium confidence*). [23.5.4, Table 23-5]
- In the Arctic, impacts on human health and well-being from climate change are significant and projected to increase, especially for many indigenous peoples (*high confidence*). Impacts include injury and risk from changes in extreme weather and ice and snow conditions; decreased access to local foods and compromised freshwater sources; permafrost and erosion damage to infrastructure; and loss of traditional livelihood, language, culture, and relocation of communities. These impacts are expected to vary among diverse settlements, and are often related to the large percentage of northern settlements along coastlines or beside rivers and lakes. [28.2.4]

Livelihoods and poverty

Climate change will create new poor, in low-income countries and middle- to high-income countries, and will jeopardize sustainable development. Most severe impacts are projected for urban areas and some regions in sub-Saharan Africa and Southeast Asia (*medium confidence,* based on *medium agreement, medium evidence*). Future impacts of weather events and climate will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas. Climate change will exacerbate multidimensional poverty in low and lower middle-income countries, including high mountain states and countries with indigenous people threatened by sea level rise and relocation, and create new poverty pockets in upper middle-

to high-income countries. Urban and wage-labor dependent poor households, as well as regions with high food insecurity, above all in Africa, and high inequality, will be particularly affected due to food price increases. [13.2.2, 13.4]

Social protection programs can help the chronically poor reduce risk and protect assets during crises, through transfers of income or assets to the poor, protection against livelihood risks, and enhancement of the social status and rights of the marginalized (*medium confidence*). However, existing projects have offered few concrete suggestions on how to address underlying social and political vulnerabilities and inequalities that inhibit adaptation. Also, there is *limited evidence* that such programs strengthen local collective capacity to act, for instance to install or modify risk-reducing infrastructure and services, or address the incapacity in local governments in provision for water, sanitation, drainage, health care, and emergency services. Existing examples underscore the need to explicitly address livelihood security and resilience in the long-term, rather than focusing on short-term disaster relief. [13.4]

Specific regional examples include:

- In North America, climate change impacts can hamper progress towards sustainability and have the potential to exacerbate existing challenges such as deficits in infrastructure or in institutional capacity to promote the health and wellbeing of human populations (*high confidence*). [26.7, 26.9]

Regional risks

Figure TS.12 provides a synthesis of sectoral risks for several regions, based on the expert judgment of assessment authors. Risks are estimated for the era of climate responsibility (here, for 2030-2040) and for the era of climate options (here, for 2080-2100) under different levels of global average warming dependent on mitigation outcomes (about +2 or +4°C global average warming above preindustrial in 2080-2100). Risks are summarized sector by sector, reflecting the overall structure of the WGII report (Part A). Risks, indicated by colored shading, are estimated for low to high adaptation to indicate opportunities for reducing risks through adaptation. Distance of this shading from the center of each diagram indicates the level of risk, with greater distance corresponding to higher risk. Examples of specific risks are presented in Table TS.5.

Assessed impacts across Europe are summarized in Table TS.6. Key regional risks for Australia and New Zealand are presented for the era of climate options in Table TS.7. Observed changes in climate and other environmental factors are shown for Central and South America in Figure TS.13. Key risks and vulnerabilities for the ocean's regions are depicted in Figure TS.14.

[INSERT FIGURE TS.12 HERE
Figure TS.12: Estimated risk from climate change to selected sectors and systems in Africa (A), Europe (B), and North America (C), for different time frames (2030-2040 and 2080-2100), under two levels of global average warming above preindustrial (2°C and 4°C) and different assumptions about adaptation to manage these risks. Levels of risk and of adaptation are differentiated by colored shading, ranging from high adaptation to low adaptation. Estimated risks rely on expert judgments. The risk categories reflect the overall structure of Part A of the WGII AR5. [Figures 22-7 and 26-6]]

[INSERT TABLE TS.5 HERE
Table TS.5: Examples of risks that increase with increasing level of climate change. Examples of potential positive impacts are also given. Risks increasing moderately or severely from now until the 2040s, which can be considered an era of climate responsibility, are described, in addition to risks increasing from ~2050 through the end of the 21st century, which can be considered to represent an era of climate options. For risks increasing in both the era of climate responsibility and the era of climate options, the potential for proactive adaptation to reduce the risks is characterized as low or high, with detail provided on adaptation issues and prospects. Risks increasing in the era of climate options can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options. Increasing risks in the era of climate responsibility are generally difficult to reduce substantially through mitigation, even with globally effective mitigation. They can be managed through vulnerability reduction, adaptation, and transformations that promote climate-resilient development pathways.]

[INSERT TABLE TS.6 HERE
Table TS.6: Assessment of climate change impacts by European sub-region and sector (by 2050, medium emissions) With economic development, with land use change. No further planned adaptation. [Table 23-4]]

[INSERT TABLE TS.7 HERE
Table TS.7: Key regional risks during the 21st century from climate change for Australia and New Zealand. Color bars indicate risk as a function of global mean temperature relative to pre-industrial, based on the studies assessed and expert judgement, for the current (top bar) and a hypothetical fully adapted state (bottom bar). For each risk, relevant climate variables and trends are indicated by symbols, in approximate order of priority. Where relevant climate projections span a particularly wide range even for a given amount of global mean temperature change, risks are shown in two pairs for high and low end projections, each without and with effective adaptation. [Table 25-8]]

[INSERT FIGURE TS.13 HERE
Figure TS.13: Summary of observed changes in climate and other environmental factors in representative regions of Central and South America. The boundaries of the regions in the map are conceptual (not precise geographic nor political) and follow those developed in SREX Figure 3-1. [Figure 27-7]]

[INSERT FIGURE TS.14 HERE
Figure TS.14: Summary of key risks and vulnerabilities associated with climate change on the world's ocean regions. [Figure 30-15]]

C.ii. Key and Emergent Risks

Key risks are potential adverse consequences for humans and social-ecological systems due to the interaction of climate-related physical hazards with vulnerabilities of societies and systems exposed. Risks are considered "key" due to high physical hazard or high vulnerability of societies and systems exposed, or both. [Box 19-2]

Key risks resulting from the interaction of hazardous climate changes and physical impacts with the vulnerability of societies and exposed systems, identified with *high confidence* [19.6.2], include the following:

- The risk for increased food insecurity can result from both local conditions like adverse changes in rainfall patterns and a lack of alternative sources of income for some affected households, as well as regional and national conditions like a breakdown of food distribution and storage processes.
- The risks of dispossession of land—including the alteration of rural inhabitants' coping and adaptation processes—result from shifts in energy policies and global markets.
- The risk of loss of livelihoods due to changes in climatic conditions and socioeconomic structures affects people living in low-lying coastal zones and people engaged in rain-fed agriculture in developing countries and countries with economies in transition.
- The risks of increasing morbidity, mortality, and infrastructure failure as well as new systemic risks (such as the risk of heat stress as a result of power shortages during extreme events) affect urban areas in both developed and developing countries.
- The risk of increase in disease burden results from the interaction of changes in physical climate conditions like increasing temperatures with the vulnerability of people due to, for example, an aging population.

Consequences of global temperature rise in excess of 4°C relative to preindustrial levels can now be assessed. See Box TS.6. Key risks associated with large temperature rise include exceedance of human physiological limits in some locations and nonlinear earth system responses (*high confidence*). There may also be key risks in other sectors and regions that have not been studied in this context. [19.5.1]

Interactions among climate change impacts in various sectors and regions, and human vulnerability and adaptation in other sectors and regions, as well as interactions between adaptation and mitigation actions, are generally not included, or not well integrated, into projections of climate change impacts. Their consideration leads to the identification of a variety of emergent risks (*high confidence*). [19.3] Several such complex-system interactions that increase vulnerability and risk are identified with *high confidence*, for example:

- The risk of severe harm and loss due to climate change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones. These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure, generating new systemic risk. [19.3.2]
- The risk of climate change to human systems is increased by the loss of ecosystem services (e.g., water and air purification, protection from extreme weather events, preservation of soils, recycling of nutrients, and pollination of crops), which are supported by biodiversity. [19.3.2]
- In some water stressed regions, groundwater stores that have historically acted as buffers against climate change impacts are being depleted, with adverse consequences for human systems and ecosystems, whilst at the same time climate change may directly increase or decrease regional groundwater resources. [19.3.2]
- Climate change adversely affects human health, increasing exposure and vulnerability to a variety of other stresses, for example by altering the prevalence and distribution of diseases that are weather and climate sensitive, increasing injuries and fatalities resulting from extreme weather events, and eroding mental health in response to population displacement. [19.3.2]
- Spatial convergence of impacts in different sectors creates impact "hotspots" involving new interactions (Figure TS.15). Examples include the Arctic (where sea ice loss and thawing disrupts transportation, buildings, other infrastructure, and potentially disrupts Inuit culture); the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification); and Sub-Saharan Africa (where global warming at the high end of the range projected for this century, i.e., more than 4°C above preindustrial levels, would be especially disruptive, resulting in high risk of reduced extent of croplands, reduced length of the growing season, increased hunger, and increased malaria transmission). [19.3.2]

[INSERT FIGURE TS.15 HERE
Figure TS.15: Some salient examples of multi-impacts hotspots identified in this assessment. [Figure 19-2]]

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change, sometimes mediated by the adaptive responses of human populations (*high confidence*). Responses to climate change can result from localized impacts that generate distant harm via responses transmitted through human or ecological systems. [19.4] Several such emergent risks are identified with *high confidence*, for example:

- Increasing prices of food commodities on the global market due to local climate impacts, sometimes in conjunction with demand for biofuels, decrease food security and exacerbate malnutrition at distant locations. [19.4.1]
- Climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states. [19.4.2]
- The possibility that climate change will alter patterns of violence is a risk emerging in the literature. The effect of climate change on conflict and insecurity has the potential to become a key risk because the reported magnitude of the influence of the climate's variability on security is large. [19.4.2]
- Shifting species ranges in response to climate change adversely affect ecosystem function and services while presenting new challenges to conservation efforts. Where range shifts cannot track climatic changes, species are at risk of eventual extinction. [19.4.2]

Additional risks have emerged recently in the literature related to particular biophysical impacts of climate change (*high confidence*). These include decreasing viability of marine calcifying organisms due to ocean acidification; increasing production and allergenicity of pollen and allergenic compounds as well as decreasing nutritional quality of key food crops due to high ambient concentrations of CO_2; and adverse regional impacts arising from Solar Radiation Management implemented for the purposes of limiting global warming. [19.5, 19.5.2, 19.5.3, 19.5.4]

The risk of crossing tipping points in socio-ecological systems may be reduced by preserving ecosystem services (*medium confidence*). Tipping points are thresholds beyond which adverse impacts increase non-linearly. Some tipping points may be avoided by limiting the level of climate change and/or removing concomitant stresses such as overgrazing, overfishing, and pollution, but there is *low confidence* in location of such tipping points and measures to avoid them. [19.7.4]

Impacts of climate change avoided under a range of scenarios for mitigation of greenhouse gas emissions are potentially large and increasing over the 21st century (*high confidence*). Advances in the assessment and implementation of mitigation measures and adaptation strategies include for the first time evaluation of avoided damages from a range of strategies. Among the impacts assessed, benefits from mitigation are most immediate for ocean acidification and least immediate for impacts related to sea level rise. Since mitigation reduces the rate as well as the magnitude of warming, it also delays the need to adapt to a particular level of climate change impacts, potentially by several decades. [19.7.1]

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). For example, no model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood, and recent findings suggest that comprehensive adaptation to current climate risk is prohibitively expensive, indicating that adaptions to future changes are similarly constrained. Assessments of stringent mitigation scenarios suggest that they can potentially avoid one half of the aggregate economic impacts that would otherwise accrue by 2100, and between 20-60% of the physical impacts, depending on sector and region. [19.7.1, 19.7.2]

The design of risk-management strategies could be informed by observation and projection systems that provide an actionable early warning signal of an approaching threshold response. However, there is *low confidence* in the feasibility and requirements for such systems, since studies to date are highly simplified and limited in number. [19.7.3]

Table TS.8 presents specific examples of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in the report. Box TS.7 integrates expert judgments about risks under the reasons for concern framework. Box TS.8 summarizes understanding of adaptation costs.

[INSERT TABLE TS.8 HERE
Table TS.8: A selection of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in the report. The examples underscore the complexity of risks determined by various climatic hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, demographic changes, or tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climate-change-related harm and loss can occur. The examples illustrate that current global megatrends (e.g., climate change, urbanization, demographic changes), in combination and in specific development contexts (e.g., in low-lying coastal zones), can generate new systemic risks that go far beyond existing adaptation and risk management capacities, particularly in highly vulnerable regions. [Table 19-3]]

Many impacts on small islands are generated from processes well beyond the borders of an individual nation or island, and generally they have negative effects (*high confidence)*. Trans-boundary impacts on small islands may originate in distant regions including continental countries and high latitudes. Examples of the former include airborne dust from the Sahara and Asia reaching small islands far down-drift from the desert source; examples of the latter include large ocean swells generated by extra tropical cyclones and high latitude low pressure systems. [29.5.1, 29.5.2] Other trans-boundary impacts result from invasive plant and animal species that reach the warmth of tropical small islands and the spread of aquatic pathogens that may have implications for human health. For island communities the trans-boundary implications of existing and future “invasions” and human health challenges are projected to increase in a changing climate. [29.3.3.2, 29.5.3, 29.5.5]

_____ START BOX TS.6 HERE _____

Box TS.6. Consequences of Large Temperature Increase (e.g., >4°C)

Projections of climate change impacts at 4°C global mean temperature increase above preindustrial indicate large impacts for physical, biological, and human systems and, in turn, large aggregate impacts for society and the global economy (*high confidence*). Global-mean surface temperatures for 2081–2100 (relative to early industrial, 1886–1905) for RCP 6.0 and 8.5 will *likely* be in the 5–95% range of the CMIP5 climate models, i.e., 2.0°C–3.9°C (RCP6.0), 3.3°C–5.5°C (RCP8.5).

For 4°C global mean temperature increase above preindustrial, the effects of climate change on water resources and ecosystems are projected to become dominant over other drivers such as population increases and land use change (*medium confidence*). Widespread coral reef mortality is projected (*high confidence*). Agricultural production is expected to decline in mid-high latitudes once local temperature rise exceeds 3°C (and for lower temperature rise in the tropics), corresponding to a global temperature rise below 4°C (*medium confidence*). Beyond 4°C there is high risk of marked yield loss even at high latitudes (*medium confidence*). Extreme heat waves such as that experienced in Russia in 2010 can become typical of a normal summer for a 4°C increase (*high confidence*). Sea level rise in a 4°C world could result in the inundation of many small island states (*high confidence*). Emerging risks include exceedance of human physiological limits in some areas for a global temperature rise of 7°C (*medium confidence*).

Sub-Saharan Africa is identified as a multi-impacts hotspot in a 4°C world, with risks of increases in hunger and disease, and of loss of ecosystem function (*high confidence*). A 4°C increase would be expected to result in non-linear earth system responses: Amazon dieback (*medium confidence*); eventual, irreversible loss of the Greenland Ice Sheet (*high confidence*); and terrestrial carbon loss due to climate-carbon cycle feedback releasing CO_2 or CH_4 (*very likely*), which would accelerate climate change further. There would also be an increased chance of triggering the collapse of the West Antarctic Ice Sheet.

[12.4, 12.5, 19.4.3, 19.5.1, 19.6.3, 19.7.5, 23.4.1, WGI AR5 SPM, 2.4.3, 8.5.3, 12.4.1, Chapter 6, Table 13.5]

_____ END BOX TS.6 HERE _____

_____ START BOX TS.7 HERE _____

Box TS.7. Anthropogenic Interference with the Climate System

Anthropogenic interference with the climate system is occurring. [WGI AR5 SPM, 10.3-10.6] The impacts of climate change[1] are already widespread and consequential. [18.3-18.6] Determining whether anthropogenic interference is dangerous involves judgments about risks.

Science can quantify risks in a technical sense, based on the probability, magnitude, and scope of potential consequences of climate change. Interpreting risks and their potential danger, however, also requires value judgments, made across scales by people with differing goals and worldviews and without full certainty of what the future will hold. Judgments about the risks of climate change depend on the relative importance ascribed to economic vs. ecosystem assets, to the present vs. the future, and to the distribution vs. aggregation of impacts. From some perspectives, isolated or infrequent damages from climate change may not rise to the level of dangerous anthropogenic interference, but accumulation of the same kinds of damages could, as they become more widespread, more frequent, or more severe. The rate of climate change can also influence risks of damages, as reflected in Article 2.

The IPCC assesses scientific and technical understanding of risks and the range of possible outcomes. It also assesses understanding of how risks are perceived, as well as methods for incorporating different value systems in decisionmaking. The IPCC cannot, however, make a determination of the level of anthropogenic interference that is dangerous.

[INSERT FOOTNOTE 1: See Box TS.2 for description of differing usage of the term “climate change” in the IPCC and UNFCCC.]

Assessment of existing frameworks pertinent to Article 2 of the UNFCCC has led to evaluations of risk being updated in light of the advances since AR4, including SREX and the current report’s discussions of vulnerability, human security, and adaptation. The management of key and emergent risks of climate change and reasons for concern includes (i) mitigation that reduces the likelihood of physical impacts and (ii) adaptation that reduces the vulnerability and exposure of societies and ecosystems to those impacts. Many of the key vulnerabilities, key risks, and emergent risks identified in this report reflect differential vulnerability between groups due to, for example, age, wealth, or income status, and deficiencies in governance, which are particularly important in assessing

risk from extreme events and risk associated with the distribution of impacts. [19.6.1, 19.6.3, 19.7]

Impacts of climate change have now been documented globally, covering all continents and the ocean (*high confidence*; Table TS.1). Detection and attribution of observed impacts of climate change supports assessments of current conditions with respect to the reasons for concern. The degree to which projected damages are now manifest, or the detection of stronger early warning signals for expected impacts, can contribute to a more comprehensive risk assessment for dangerous anthropogenic interference with the climate system. [18.6.2]

Updating of the reasons for concern (Box TS.7 Figure 1) leads to the following assessment:

- Unique human and natural systems tend to have very limited adaptive capacity, and hence we have *high confidence* that climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C over preindustrial levels were exceeded. In addition, there is new and stronger evidence to support the previous judgment of *high confidence* that a warming of up to 2°C above 1990-2000 levels would result in significant impacts on many unique and vulnerable systems, and would likely increase the endangered status of many threatened species, with increasing adverse impacts and increasing risk of extinctions (and increasing confidence in this conclusion) at higher temperatures. There is higher confidence in observed impacts on Arctic marine and terrestrial ecosystems and indigenous livelihoods (*medium to high confidence*), tropical coral reefs (*high confidence*) and glaciers in most mountain regions (*high confidence*). [18.6.2, 19.6.3]
- The overall risk from extreme events due to climate change has not changed significantly since AR4, but there is higher confidence in the attribution of some types of extreme events to human activity and in the assessment of the risk from extreme events in the coming decades. In addition, there is a new appreciation for the importance of exposure and vulnerability, in both developed and developing countries, in assessing risk associated with extreme events. [19.6.1, 19.6.3]
- Risk associated with the distribution of impacts is generally greatest in low-latitude, less developed areas, but because vulnerability is unevenly distributed within countries, some populations in developed countries are highly vulnerable to warming of less than 2°C, as noted in AR4 (*high confidence*). [19.6.3]
- Globally aggregated risk is underestimated because it does not include many non-monetized impacts, such as biodiversity loss, and because it omits many known impacts that have only recently been quantified, such as reduced labor productivity (*high confidence*). In addition, aggregated estimates of costs mask significant differences in impacts across sectors, regions, countries, and populations (*very high confidence*). The overall assessment of aggregate risk and confidence in that assessment has not changed since AR4. [19.6.3]
- The risk associated with large-scale singular events such as the at least partial deglaciation of the Greenland ice sheet remains comparable to that assessed in AR4. [19.6.3]

[INSERT BOX TS.7 FIGURE 1 HERE
Box TS.7 Figure 1: The dependence of risk associated with reasons for concern (RFCs) on the level of climate change, updated based on expert judgment in this assessment. The color scheme indicates the additional risk due to climate change (with white to purple indicating the lowest to highest level of risk, respectively). Purple color, introduced here for the first time, reflects the assessment that unique human and natural systems tend to have very limited adaptive capacity. [Figure 19-5]]

The determination of key risks as reflected, for example, in the reasons for concern in the Third and Fourth Assessment Reports did not distinguish between alternative development pathways. The development of risk profiles from Shared Socioeconomic Pathways and Representative Concentration Pathways is an important area of research that can lead to improvement in the framework developed in this report. [19.6.3]

_____ END BOX TS.7 HERE _____

_____ START BOX TS.8 HERE _____

Box TS.8. Adaptation Costs

Estimates of the global costs of adaptation continue to improve, but remain inconsistent in methods, sectoral coverage, purposes, and time frames. The most recent estimates suggest a range from 75 to 100 US$ billion per year globally by 2050 (*low confidence*), but important omissions from these estimates suggest the high end of this range could be much higher, and important shortcomings in the data and methods available for costing adaptation suggest the low end of this range could be substantially lower.

- Defining the benefits and cost of adaptation is difficult, is limited by data, and depends on value judgments. Estimating adaptation costs poses methodological, practical, and moral difficulties, with consequences for how adaptation can be funded. [17.3.6, 17.3.10, 17.3.11, 17.6]
- The existing estimates of global adaptation costs could be higher if sectors such as ecosystems and tourism and socially contingent effects are included, and if the adaptation deficits of developing countries are more fully taken into account. The global figures are based on only a few lines of evidence and cover a selected number of sectors. [17.6]
- Some evidence suggests that incremental adaptation costs increase over time as climate change unfolds (*low confidence*), but consideration of current adaptation deficits suggests that costs could be high in the short-term as well, and inconsistencies in the effect of economic development on adaptation capacity also confound the reliability of estimates of the trend over time. [17.6.3]

Adaptation costing studies suffer from the absence of a robust community of practice, with great inconsistencies in the purposes, methods, data quality, and sectoral coverage of these analyses, limiting attempts to aggregate the finer-scale study results across regions and time. Among these regional and local-scale analyses desirable characteristics include: a broad representation of relevant climate stressors to ensure robust economic evaluation; consideration of multiple alternative and/or conditional groupings of adaptation options; rigorous economic analysis of costs and benefits across the broadest possible market and nonmarket scope; and a strong focus on support of practical decision-making that incorporates consideration of sources of uncertainty. Few current studies manage to achieve all of these objectives. [17.6.3]

_____ END BOX TS.8 HERE _____

_____ START BOX TS.9 HERE _____

Box TS.9. Ocean Acidification

Anthropogenic ocean acidification (Box TS.9 Figure 1A) and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide. [WGI AR5 2.2.1] The fundamental chemistry is well understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected with high accuracy from projections of atmospheric CO_2 levels in the open ocean, but not in coastal waters where eutrophication and upwelling contribute to local ocean acidification. [5.3.3.6, 30.5.4]

Ocean acidification occurs on a backdrop of other environmental changes, both global (e.g. warming, decreasing oxygen levels) and local (e.g. pollution, eutrophication), yet their combined impacts remain poorly understood. A pattern of impacts—some positive, others negative—emerges for some processes and organisms (*high confidence*; Box TS.9 Figure 1B), but key uncertainties remain from organismal to ecosystem levels. A wide range of sensitivities exists within and across organisms, with higher sensitivity in early life stages. [6.2.4] Lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers, reducing their competitiveness with non-calcifiers (*high confidence*; Chapters 5, 6, and 30). Growth and primary production are stimulated in seagrasses and some phytoplankton (*high confidence*), and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Adult fish remain relatively undisturbed by elevated CO_2, although serious behavioral disturbances have been reported in larval and juvenile reef fishes. [6.2.4] Natural analogues at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity of communities living on the sea floor. Shifts in

organisms' performance and distribution will change both predator-prey and competitive interactions, which could impact food webs and higher trophic levels (*limited evidence, high agreement*). [6.3]

A few studies provide *limited evidence* for adaptation in phytoplankton and mollusks. However, mass extinctions during times in Earth history with much slower rates of ocean acidification suggest that evolutionary rates are too slow for sensitive species to adapt to the projected rates of change (*high confidence*). [6.1.2]

The biological, ecological, and biogeochemical changes driven by ocean acidification will affect key ecosystem services. The oceans will become less efficient at absorbing CO_2 and hence moderating climate (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will diminish their role in shoreline protection as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*). [Box CC-CR] The global cost of production loss of mollusks could be over 100 billion USD by 2100. The largest uncertainty is how the impacts on prey will propagate through marine food webs. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic, and/or synergistic interactions will occur with other environmental and human factors.

[INSERT BOX TS.9 FIGURE 1 HERE
Box TS.9 Figure 1: A) Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options. B) Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted. The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect. [Box CC-OA]]

_____ END BOX TS.9 HERE _____

D) BUILDING RESILIENCE THROUGH MITIGATION, ADAPTATION, AND SUSTAINABLE DEVELOPMENT

This section evaluates the ways that human and social-ecological systems can build resilience through mitigation, adaptation, and sustainable development. It assesses understanding of climate-resilient pathways and of incremental versus transformational changes, and it considers co-benefits, synergies, and tradeoffs among mitigation, adaptation, and development.

D.i. Climate-resilient Pathways and Transformation

Climate change calls for new approaches to sustainable development that take into account complex interactions between climate and social-ecological systems (see Figure TS.16). Climate-resilient pathways for development are rooted in iterative processes of identifying vulnerabilities to climate change impacts; taking appropriate steps to reduce vulnerabilities in the context of development needs and resources and to increase the options available for vulnerability reduction and coping with surprises; monitoring emerging climate parameters and their implications, along with monitoring the effectiveness of vulnerability reduction efforts; and revising risk reduction responses on the basis of continuing learning. This process may involve a combination of incremental changes and, as necessary, significant transformations. [20.2.3.1, 20.6.2]

[INSERT FIGURE TS.16 HERE
Figure TS.16: Conceptual framework for assessing interactions between biophysical and societal stressors that impact the resilience of natural and human systems today and in the future. Actions, including climate change adaptation and mitigation, taken in the opportunity space lead to a diverse range of pathways and outcomes—toward a future of high risk, high vulnerability, and low resilience space or toward a future of low risk, low vulnerability, and high resilience space. [Figure 1-7]]

Assessment findings integrate a variety of complex issues in assessing climate-resilient pathways in a variety of regions at a variety of scales: sustainable development as the ultimate aim, mitigation as the way to keep climate change impacts moderate rather than severe, adaptation as a response strategy to cope with impacts that cannot be (or are not) avoided, and elements of sustainable development pathways that contribute to climate-resilience. In most cases, vulnerability reduction and appropriate risk management approaches will differ from situation to situation, calling for a multi-scale perspective. But most situations share at least one fundamental characteristic: threats to sustainable development are greater if climate change is substantial than if it is moderate.

The findings are based on a high level of consensus in source materials and in the expert communities, although the amount of supporting evidence is usually limited by the fact that so many aspects of sustainable development and climate change mitigation and adaptation, considered together over periods many decades into the future, are surrounded by issues that are beyond past and current observation and experience. The task of this part of the assessment is to move out into uncharted territory.

Because climate change is a growing threat to development, it is a high priority to identify and pursue climate-resilient pathways for sustainable development (*high confidence* based on *high agreement, medium evidence*). Added to other stresses on sustainable development, effects of climate change will make sustainability more difficult to achieve for many locations, systems, and affected populations, related to such objectives as poverty reduction, health, and livelihood security; but climate-resilient pathways can improve prospects for sustainable development. [20.2]

Climate-resilient pathways include (a) actions to reduce climate change and its impacts and (b) actions to assure that effective risk management and adaptation can be implemented and sustained (*high confidence*, based on *high agreement, medium evidence*). Adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses. Both kinds of responses are needed, working together to reduce risks of disruptions from climate change. [20.3, 20.4]

In some cases, each of the two categories of responses can benefit the other as well, offering potentials for co-benefits from integration (*medium* to *high confidence,* based on *medium* to *high agreement, medium evidence*). Development pathways that are resilient with respect to a wide range of challenges and threats are more likely to be climate-resilient, while climate change risk reduction can contribute to strengthening capacities for risk management in other regards as well. Strategies to achieve each goal have the potential to reinforce the other, but windows of opportunity may narrow with time. [20.2.1, 20.3.3]

Paying attention to dynamic livelihoods and multidimensional poverty and the multifaceted impacts of climate change and climate change responses is central to achieving climate-resilient development pathways (*high confidence*). Business-as-usual development and climate policies will bring the poor and the marginalized precariously close to the two most undesirable future scenarios as conceptualized in the shared socio-economic pathways (SSPs): social fragmentation (fragmented world) and inequality (unequal world). Global inequality has been increasing, with new poverty pockets emerging in middle- and high-income countries and shifts from transient to chronic poverty, while at the level of communities, elite capture and unsupportive policy structures often propel less affluent households into deeper poverty. [13.4]

Avoiding limits to adaptation is a complex management challenge necessitating new integrative forms of risk governance (*medium agreement, limited evidence*). Limits to adaptation are influenced by cultural, institutional, and socio-economic factors. Consequently, avoiding limits will necessitate policy responses and awareness that goes beyond greenhouse gas mitigation and adaptation responses alone. Driving forces such as inequality and the disproportionate vulnerability of marginalized actors to climate-related disasters and catastrophic losses will need to be addressed. Hence, a portfolio of local, national, and international strategies will be needed to facilitate sustainable development that expands the range of climate to which socio-ecological systems can adapt. [16.4, 16.6, 16.7]

Prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation (*high confidence,* based on *high agreement, medium evidence*). As the magnitude of climate change grows, the challenges to climate resilience grow; and above some high level of climate change, the impacts on most systems would be great enough that climate-resilience is no longer possible for many systems and locations (see Box TS.10). [20.6.1]

Because climate change vulnerabilities are significant for many areas, systems, and populations, climate-resilient pathways will often require transformations in order to assure sustainable development (*high confidence,* based on *high agreement, medium evidence*). Significantly large and/or rapid increases in extreme weather and climate events are less amenable to incremental adaptations to climate change and will often require more transformational change if development is to be sustained without major disruptions (see Box TS.10). [20.5]

At a global scale, climate-resilient pathways will include both climate change adaptation and mitigation. At sub-global scales, climate-resilient pathways will involve a range of actions appropriate to potentials for vulnerability/risk reduction at those scales (*high confidence,* based on *high agreement, medium evidence*). Although at a global scale both mitigation and adaptation are essential, relatively local scales in many developing regions have limited capacities to include mitigation in their climate-resilience strategies because they contribute very little to the causes of climate change. At all scales, however, actions are important to assure that effective risk management can be implemented and sustained. [20.2.3, 20.6.1]

D.ii. Examples of Co-benefits, Synergies, and Tradeoffs

Responses to the risks of climate change can have implications beyond their primary objectives for the resilience of societies and systems.

Example interactions among impacts and adaptation responses

Adaptation designed for one sector may interfere with the functioning of another sector, creating new risks (*high confidence*). For example, increasing crop irrigation in response to a drying climate can exacerbate water stress in downstream wetlands, where the latter otherwise provide important water cleaning services (*high*

confidence). Examples of potential trade-offs among adaptation objectives are provided in Table TS.9. [4.3.3, 4.3.4, 19.3.2]

[INSERT TABLE TS.9 HERE
Table TS.9: Examples of potential trade-offs among adaptation objectives. [Table 16-2]]

Example interactions among impacts and mitigation responses

Certain approaches to reduce greenhouse-gas emissions imply greater risks for freshwater systems than others (*high agreement, limited evidence*). Bioenergy crops can require larger amounts of water for irrigation than the amount of water for other mitigation measures. Hydropower has negative effects on freshwater ecosystems that can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk. [3.7.2]

Use of the terrestrial biosphere in climate mitigation actions, such as through introduction of fast-growing tree species for carbon sequestration or the conversion of forest to biofuel plantations, may lead to negative impacts on ecosystems and biodiversity (*very high confidence*). The land use scenario accompanying the mitigation scenario RCP2.6, intended to avoid 2°C global warming, features large expansion of biofuel production displacing natural forest cover. [4.2.4]

Achieving emission targets without putting a price on carbon emissions from land-use has the potential to lead to very large reductions in forested area, and much higher overall costs for mitigation, compared to meeting the same targets while putting a price on all carbon emissions. Similarly, substantial regional variation in the availability of technologies exists, but the differences in how these are represented regionally are largely unexplored. [21.5.3]

There are opportunities to both reduce emissions of climate altering pollutants and at the same time improve local health in the communities that take action, as well as protecting health for populations worldwide through climate change abatement. Among others, mitigation-related actions with health co-benefits include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy production and use in households and communities, through better combustion, energy efficiency, and a shift to cleaner renewable energy sources (*very high confidence*). [11.9]
- Providing access to reproductive health services and thus improving child and maternal health through increased birth spacing, while reducing population growth and consequent climate altering pollutant emissions over time (*high confidence*). [11.9]

Example interactions among mitigation, adaptation, and development

Climate policies, such as encouraging cultivation of biofuels and payments under REDD, will result in mixed and potentially detrimental impacts on land-use and on the livelihoods of poor and marginalized people (*medium confidence*). Mitigation efforts such as CDM and REDD+, as well as land acquisition for food and biofuel production, show preliminary negative impacts on the poor, particularly indigenous people and (women) smallholders. In rural areas, secondary impacts and trade-offs between mitigation and adaptation have implications for governance. Insurance schemes, social protection programs, and disaster risk reduction may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty. Climate-resilient development pathways will have only marginal effects on poverty reduction, unless structural inequalities are removed and needs for equity among the poor and non-poor met. [9.3.3, 13.3.1, 13.3.2, 13.4.1, 13.4.2]

In Europe, there are opportunities for policies that improve adaptive capacity and also help meet mitigation targets (*high confidence*). Some agricultural practices can potentially mitigate GHG emissions and at the same time adapt crops to increase resilience to temperature and rainfall variability. Climate policy in transport and energy sectors to reduce emissions can improve population health. However there is also potential for unintended consequences of mitigation policies in the built environment (especially housing) and energy sectors. [23.8]

In Asia, multiple stresses caused by rapid urbanization, industrialization, and economic development will be compounded by climate change (*high confidence*). Climate change is expected to adversely affect sustainable development capabilities of most Asian developing countries by aggravating pressures on natural resources and the environment. Development of sustainable cities in Asia with fewer fossil fuel driven vehicles and with more trees and greenery would have a number of co-benefits including for public health. [24.4, 24.5, 24.6, 24.7]

For Australasia, significant synergies and trade-offs exist between alternative adaptation responses, and between mitigation and adaptation responses; interactions occur both within Australasia and between Australasia and the rest of the world (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, and biodiversity, but tools to understand and manage these interactions remain limited. Flow-on effects from climate change impacts and responses outside Australasia have the potential to outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*), but they remain amongst the least explored issues. [25.7.5, 25.9.1, 25.9.2, Box 25-10]

Throughout North America, adaptation actions at the local level have the potential to result in synergies, conflicts, or tradeoffs with mitigation and other development actions and goals (*high confidence*). For example, reductions in emissions of greenhouse gases will in many cases bring proximal benefits for human health by reducing health-damaging air pollution concentrations. Conversely, sea walls can protect coastal properties, yet may negatively affect the structure and function of coastal ecosystems. [26.8]

In Central and South America, long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the population. Such conditions weaken the importance of adaptation planning to climate change on the political agenda. Various examples demonstrate possible synergies between development, adaptation, and mitigation planning, which can help local communities and governments to allocate efficiently available resources in the design of strategies to reduce vulnerability. [27.3.4, 27.4.1, 27.4.2, 27.4.3, 27.4.4, 27.5].

In Central and South America, renewable energy has a potential impact on land use change and deforestation, but at the same time will be an important means of adaptation, particularly in Southeastern South America. Hydropower is currently the main source of renewable energy in Central and South America, followed by biofuels, notably bioethanol from sugarcane and biodiesel from soy. Southeastern South America is one of the main sources of production of the feedstocks for biofuels' production. Sugarcane and soy are *likely* to respond to the elevation of CO_2 and temperature with an increase in growth, which might lead to an increase in productivity and production. However, the drought effects expected for some regions in Central and South America will be critical, and scientific knowledge has to advance in this area. Advances in second generation bioethanol from sugarcane and other feedstocks will be important as a measure of adaptation, as they have the potential to increase biofuels productivity in the region. In spite of the large amount of arable land available in the region, the expansion of sugarcane and soy, related to biofuels production, might have some indirect land use change effects, producing teleconnections that could lead to deforestation in the Amazon and loss of employment in some countries. This is especially derived from the expansion of soy, which is used for biodiesel production inclusively. [27.3.6]

For small islands, adaptation and mitigation are not trade-offs, but can be regarded as complementary components in the response to climate change (*medium confidence*). For most small islands climate change is just one of a series of multiple stresses that must be coped with, and often it is not the most important one. Three key areas for adaptation-mitigation inter-linkages in small islands are identified: energy supply and use, tourism infrastructure and activities, and coastal wetlands. The alignment of these sectors for potential emission reductions together with adaptation needs offers co-benefits and opportunities in small islands. Lessons learned from adaptation and mitigation experiences in one island may offer some guidance to other small island states, though we have *low confidence* in the wholesale transfer of adaptation and mitigation options when the lenses through which they are viewed differ from one island state to the next, based on cultural, socio-economic, ecological, and political values. [29.6.2.1, 29.7.2, 29.8, 29.3.3]

For small islands, assistance from the international community is vital for supporting adaptation and mitigation programs, though there is increasing concern that some types of interventions may be maladaptive (*high agreement, medium evidence*). Caution is needed to ensure that donors are not driving the climate change

agenda in small islands, as there is a risk that donor-driven adaptation and mitigation aid may not address the critical challenges confronting island governments and communities, and may not be aligned with the sustainable development goals of small islands. This may lead to inadequate adaptation or a waste of scarce resources and may unintentionally cause enhanced vulnerability by supporting inappropriate adaptation strategies that are externally derived, rather than optimizing the benefits of local practices that have proven to be efficacious through time. [29.8, Box 29-1, 29.6.2.3, 29.6.3]

Table TS.10 provides further specific examples of interactions to complement the assessment findings above.

[INSERT TABLE TS.10 HERE
Table TS.10: Illustrative examples of intra-regional interactions among adaptation, mitigation, and sustainable development.]

_____ START BOX TS.10 HERE _____

Box TS.10. Adaptation Limits and Transformation

Adaptation can expand the capacity of natural and human systems to cope with a changing climate. However, there are limits to adaptation that, when exceeded, prevent the achievement of management goals or the maintenance of societal values. Such limits are context-specific and subject to uncertainty. Therefore, they are best considered in a risk management context that focuses on the values and objectives of actors. This allows limits to be defined as the point at which an actor's objectives (or biophysical system needs) cannot be secured from intolerable risks through adaptive actions (see Box TS.10 Figure 1). [16.2, Box 16-2] The determination of what constitutes an intolerable risk is made by actors at different scales of governance through processes of deliberation and social learning. Beyond a limit, there must be a change in objectives or needs, else actors will experience an escalating risk of loss and damage. [16.2, 16.4.3, 20.5, 20.6.1]

Limits to adaptation can arise from a diverse array of factors. The rate and magnitude of climate and socioeconomic changes are key determinants of adaptation limits, as they influence the vulnerability of natural systems as well as their capacity to respond. [16.3.1] The Representative Concentration Pathways and Shared Socioeconomic Pathways, for example, represent a broad range of greenhouse gas emissions futures and socioeconomic development storylines. [Box 20-3] The greater the rate and magnitude of climate change, the more likely limits to adaptation will be exceeded. [16.4.2, 20.5.1] Limits also arise from the subjective values of societal actors, which influence both the demand for adaptation and the perceived appropriateness of specific policies and measures. [16.2, 16.3.1, 16.3.4, 16.4.1] While limits fundamentally imply that adaptation can no longer avoid intolerable impacts, they can be viewed as "soft" if there are opportunities for impacts to be reduced over time through, for example, changes in laws, institutions, or values or the emergence of new technologies. [16.4.1] In contrast, "hard" limits are those which cannot be reduced through human agency and tend to be associated with biophysical processes, such as climate thresholds in natural systems. [16.4.1]

The Earth System is committed to some climate change in the future, and some degree of loss and damage may be inevitable. [20.5.1] Considering that climate change can include large-scale discontinuities and irreversible adverse consequences, the existence of limits to adaptation suggests greater attention to deliberate transformational change is needed. Such transformations, defined as fundamental changes in the attributes of a system, can occur through social and technological innovations or changes in behavior or institutions, but often they involve changes in political, economic, social, cultural or legal systems, as well as changes in individual and collective beliefs, values, and worldviews. [20.5.2] As such, transformational change may trigger societal debate over the acceptability of risk, mitigation, and adaptation strategies in order to reconcile conflicting goals and visions of the future while placing new and increased demands on governance structures at multiple levels.

[INSERT BOX TS.10 FIGURE 1 HERE
Box TS.10 Figure 1: Conceptual model of the determinants of acceptable, tolerable, and intolerable risks and their implications for limits to adaptation. [16.2, Figure 16-1]]

_____ END BOX TS.10 HERE _____

WGII Frequently Asked Questions

Chapters of the report supporting each FAQ are provided in square brackets.

1. Are we seeing impacts of climate change?

Yes, many climate-change impacts are already apparent. Impacts of recent observed climate change on physical, biological, and human systems have been detected on all continents and in most oceans. We have *medium* to *very high confidence* that several regions have experienced warming trends and more frequent high-temperature extremes. We have *high* to *very high confidence* that, due to rising temperatures, hydrological cycles have been disrupted by decreased snowpack, degradation of permafrost regions, and diminishing glaciers. Moreover, many ecosystems are experiencing climate-induced shifts in the activity, range, or abundance of the species that inhabit them, leading to changes in ecosystem function. There is emerging evidence that oceans are also displaying changes in physical and chemical properties that, in turn, are affecting coastal and marine ecosystems such as coral reefs, and other oceanic organisms such as crustaceans and zooplankton. Crops and other managed ecosystems are seeing changes as well. While crop yields and fishery stocks are sensitive to changes in temperature; only *limited evidence* confirms a role of climate change in crop and fish production.

[Chapters 3, 4, 5, 6, 7, 18, 22, 24, 25, 27, and 30; SPM]

2. Has climate change already affected food production?

Changes in crop and aquaculture production are sensitive to both climatic drivers and non-climatic socioeconomic drivers, making it difficult to isolate the changes caused by climate change. However, there is emerging evidence that agricultural crop yields are changing in many regions in response to climate. For example, there is *medium confidence* that declines attributable to climate change have been observed in the yields of wheat crops of some European countries. Moreover, there is *high confidence* that extreme heat has a negative effect on food nutritional quality. There is emerging evidence that other parts of the Earth system altered by climate change, (e.g. atmospheric CO_2, tropospheric ozone, and water and nitrogen cycles) can alter food production in complex ways. Hence, climate change will continue to affect food systems, with impacts that are widespread, complex, and varying over space and time.

[Chapters 6, 7, 18, 19, 22, and 23]

3. Is climate change bad news for everyone or will there be winners and losers?

Of the many climate-change impacts assessed in this report, only a few are positive. They will not be felt equally around the world. There is *very high confidence* that climate changes interact with vulnerability and exposure to shape differential risks and impacts. Climate change can act as a threat multiplier for those at the social or economic margins or in unfavorable locations. Climate change will have different implications for people across the world, with impacts that vary over time and depend on the rate and magnitude of climate change. For example, there is *medium* to *high confidence* that some countries will have increased opportunities for economic development, reduced instances of some diseases, or expanded areas of productive land. Other countries will face increased challenges for economic development, increased risks of some diseases, or degraded ecosystems. There is *medium confidence* that crop yields will vary by latitude, with yield losses in the tropics. In temperate regions, climate change could stimulate yield increases over the next few decades but decrease them after that. There is *high confidence* that the potential global catch for fisheries will change, with both positive and negative consequences from climate-induced impacts on ocean mixing and shifts in species range.

[Chapters 4, 6, 7, 10, 11, 13, 22, 25, and 30]

4. What aspects of ecosystems will change due to climate change, and how will that affect communities?

There is *high confidence* that many ecosystems are sensitive to climate change, interacting with other human activities. Changes in ecosystems influence society through diverse effects on available natural resources and ecosystem services. For example, there is emerging evidence that reductions in fish stocks will affect the livelihoods

of fishing communities, as well as food security for those that rely on fish. There is *medium* to *high confidence* that ecosystem impacts can include losses of carbon, increased likelihood of the establishment and spread of invasive alien species, and loss of valuable biodiversity, disrupting ecosystem services that contribute towards the quality of human life.

[Chapters 4, 19, and 30]

5. What are key vulnerabilities, and what kinds of factors contribute to them?

Key vulnerabilities are those that have the potential to combine with climate-change impacts to result in severe consequences for society or social-ecological systems. Seven factors contribute to a key vulnerability. These are:

- the exposure of societies, communities, or social-ecological systems to climatic stressors
- the probability that these would experience major harm, loss, and damages
- the importance of the vulnerable systems
- the limited ability of societies or communities to cope with the climate-related hazards within existing capacities
- the limited ability of societies or communities to build adaptive capacities to reduce or limit vulnerability as environmental and climatic conditions change
- the persistence of vulnerable conditions and degree of irreversibility of consequences
- the presence of conditions that make societies highly susceptible or sensitive to cumulative stressors in complex, interacting systems

[Chapter 19]

6. Does climate change cause violent conflicts?

There is *medium confidence* that some factors that increase the risk of violent conflicts and civil wars are sensitive to climate change. *Robust evidence* demonstrates that low per capita incomes, economic contraction, and inconsistent state institutions, all of which are sensitive to climate change, are associated with the incidence of civil wars. There is little agreement about whether these factors cause violent conflicts. Climate-change policies, particularly those associated with changing property rights, can increase the risk of violent conflict. Policies and institutions at multiple scales that encourage economic growth, high per capita incomes, strong democratic institutions, social protection during economic and climate shocks, and robust institutional structures that protect property rights and manage conflicts reduce the risk that climate variability and extremes will lead to violence.

[Chapter 19]

7. How is ocean acidification related to climate change and how does it affect marine and coastal areas?

Ocean acidification is a consequence of increased atmospheric CO_2. This leads to a net transfer of CO_2 from the atmosphere to the oceans, resulting in an increase in dissolved CO_2 and a reduction in pH. Seawater with higher dissolved CO_2 has lower concentrations of dissolved carbonate ion, the building block for shells and skeletons of many marine organisms. There is *high confidence* that seawater acidity (pH) has numerous implications for ocean and coastal processes and organisms, including rates of primary production, the deposition of calcium carbonate in shells and skeletons, and the degradation of limestone.

[Chapter 5; Cross-chapter Box, Ocean Acidification]

8. What communities are most vulnerable to impacts of climate change?

Every society is vulnerable to the threats from climate change, although the nature of that vulnerability varies across regions and communities, and over time. Poorer communities tend to be more vulnerable to loss of life, while wealthier communities have more economic assets at risk. There is *high confidence* that differences among communities in age, race and ethnicity, socio-economic status, and governance have had significant influence on the outcome of past weather and climate extremes. Regions affected by violence or governance failure are particularly

vulnerable. Other development challenges, such as gender inequality and low levels of educational attainment, also make communities vulnerable to climate change.

[Chapters 9, 10, 19, 26, and 27]

9. How are adaptation, mitigation, and sustainable development connected?

Adaptation, mitigation, and sustainable development are intrinsically related to each other in the context of climate change. Mitigation reduces the likelihood of physical impacts. Adaptation reduces the vulnerability and exposure of societies and ecosystems to those impacts. Together, both responses help define climate-resilient pathways that contribute to long-term sustainable development. There is *very high confidence* that interactions between adaptation and mitigation responses have both potential synergies and tradeoffs that vary according to context. There are many examples of the potential for co-benefits, but there are also examples of competitive relationships between adaptation and development, which, when poorly implemented, can aggravate the condition of vulnerable communities. Integrating adaptation, mitigation, and sustainable development simultaneously in long-term planning has the potential to amplify the benefits of each.

[Chapters 9, 13, 17, 19, 20, 25, and 29]

10. Why is it difficult to attribute observed changes to climate change?

Attribution addresses the question of whether observed changes were caused by climate change. The main challenge in attribution is separating the role of climate change from the roles of other factors. For example, widespread flooding in Australia and other parts of the western Pacific during 2010 and 2011 was caused by unusually heavy rainfall. This was related to La Niña conditions. La Niña is part of the naturally occurring ENSO variation, making it impossible, based on the available evidence, to attribute the flooding to climate change. In human systems, attributing observed changes to climate change is complicated by interactions with the effects of economic and social factors. The emerging literature discussing the relationship between climate change and poverty, working conditions, violent conflict, migration, and economic growth has many examples, but unequivocal attribution remains a challenge.

[Chapter 18]

11. Are risks of climate change mostly due to changes in extremes, changes in average climate, or both?

People and ecosystems across the world experience climate in many different ways. Average climate conditions are important. They provide a starting point for understanding how far ecosystems extend north and south, and for informing decisions about tourist destinations, other business opportunities, and crops to plant. But weather and climate extremes strongly influence losses and dislocations. Crops can fail following flood or drought. Buildings constructed to stricter codes are more likely to weather the waves or winds of a storm. And forests burn when high winds combine with low humidity. In a changing climate, many impacts for people, ecosystems, activities, and infrastructure will occur due to changes in the intensity, frequency, or duration of weather and climate extremes.

[Chapters 2, 4, 7, 8, 9, 10, 12, 13, 20, and 25; TS]

12. How much do we know about the world in 2100?

People can often guess what tomorrow might bring. But anticipating the future 5, 10, or 50 years out is increasingly difficult. On the scale of decades, technological revolutions, political movements, or singular events can shape the course of history in unpredictable ways. To understand potential impacts of climate change for societies and ecosystems at the end of this century, scientists use a variety of approaches. One is recognizing consequences of some intrinsic limits. The total amount of land or the number of species of mammals will not increase, for example. Another opportunity builds on simple relationships that have been robust over long periods. Scenarios are internally consistent descriptions of possible futures, reflecting factors like possible population growth, investments in technology, and commitments to protecting the environment. Over timeframes of a few years to as much as a century, they provide powerful means of exploring the implications of decisions that affect people, ecosystems, and

economies. Scenarios can also link patterns of greenhouse gas emissions to underlying societal and economic trends, bridging from decisions to their consequences for climate.

[Chapters 1, 2, 4, 6, 17, 20, and 21; TS]

13. Why is climate change a challenge of managing risks?

For individuals, enterprises, or nations, success can hinge on making good decisions under uncertainty. Effective decisionmaking under uncertainty considers outcomes that are highly likely, but it also considers less probable outcomes that would have big consequences. As the WGII AR5 demonstrates, we know a great deal about impacts of climate change that have already occurred, and we understand many aspects of impacts projected for the future. But impacts of climate change also involve uncertainties, including some that are persistent. Future emissions of greenhouse gases will depend on societal decisions not yet made. Modeling future climate change and impacts entails uncertainties due to variability in Earth's physical systems and ecosystems and due to limits of current scientific understanding. We also have limited ability to characterize fully the resilience of people and ecosystems experiencing impacts. Good decisions about avoiding or managing the consequences of climate change build on available information, recognizing the value of timely investments and actions, even with consequential uncertainty. Managing risks positions societies, economies, and ecosystems to capitalize on the upside outcomes of climate change, while preparing for the full range of possible downside outcomes.

[Chapters 1, 2, 17, 19, 20, 21, and 25; TS]

14. What are the timeframes for mitigation and adaptation benefits?

Adaptation can reduce the damage from impacts that cannot be avoided. Mitigation strategies can decrease the amount of climate change that occurs, as summarized in the WGIII AR5. But the consequences of investments in mitigation emerge incrementally, not immediately. Over the next few decades, the climate change we experience will be determined primarily by the combination of past actions and current trends in greenhouse gas emissions. The next few decades are, in essence, an era of climate responsibility, where short-term risk reduction comes from adapting to the changes already underway, while we also take responsibility for the leverage of mitigation on the potential for climate change in the latter decades of the century, the era of climate options.

[Chapters 1, 2, 16, 19, 20, and 21; TS]

15. Can science identify thresholds beyond which climate change is dangerous?

Anthropogenic interference with the climate system is occurring. The impacts of climate change are already widespread and consequential. Determining whether anthropogenic interference is dangerous involves judgments about risks. Science can quantify risks in a technical sense, based on the probability, magnitude, and scope of potential consequences of climate change. Interpreting risks and the scale at which they become dangerous, requires value judgments, made by people with differing goals and worldviews and without full certainty of what the future will hold. Judgments about the risks of climate change depend on the relative importance ascribed to the present vs. the future, to economic vs. cultural, natural, and aesthetic assets, and to global GDP versus the interests of the most vulnerable. Isolated or infrequent damages from climate change may not rise to the level of dangerous anthropogenic interference, but accumulation of the same kinds of damages could, as they become more widespread, more frequent, or more severe. The IPCC assesses scientific and technical understanding of risks and the range of possible outcomes. It also assesses understanding of how risks are perceived, as well as methods for incorporating different value systems in decisionmaking. The IPCC cannot, however, make a determination of the level of anthropogenic interference that is dangerous.

[Chapters 1, 2, 4, 5, 6, 17, 18, 19, and 25; TS]

WGII CROSS-CHAPTER BOXES

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based approaches to adaptation (also termed Ecosystem-based Adaptation, EBA) integrate the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe *et al.*, 2011; Munroe *et al.*, 2011). EBA is implemented through the sustainable management of natural resources, as well as conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls *et al.*, 2009). The CBD COP 10 Decision X/33 on Climate Change and Biodiversity states further that effective EBA also "takes into account the multiple social, economic and cultural co-benefits for local communities".

The potential for EBA is increasingly being realized (e.g., Munroe *et al.*, 2011), offering opportunities that integrate with or even substitute for the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees, may adversely affect biodiversity, resulting in maladaptation due to damage to ecosystem regulating services (Campbell *et al.*, 2009, Munroe *et al.*, 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). Well-integrated EBA is also more cost effective and sustainable than non-integrated physical engineering approaches, and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. EBA also offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes.

EBA provides opportunities particularly in developing countries where economies depend more directly on the provision of ecosystem services (Vignola *et al.*, 2009), to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang *et al.*,). In these settings, ecosystem-based adaptation projects may be readily developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan *et al.*, 2012, Midgley *et al.*, 2012; Roberts *et al.*, 2012)

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Midgley *et al.*, 2012, Opperman *et al.*, 2009).
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands and deltas) to provide effective measure against storm-surges, saline intrusion and coastal erosion;
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding;
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques;
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

It is important to assess the appropriate and effective application of EBA as a developing concept through learning from work underway, and to build understanding of the social and physical conditions that may limit its effectiveness. Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach.

[INSERT FIGURE EA-1 HERE

Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems,

ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.]

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Box CC-CR. Coral Reefs

[Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building (scleractinian) corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics. About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and are likely to derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including those from provisioning (food, construction material, medicine), regulating (shoreline protection, water quality), supporting services (oxygen supply) and cultural (religion, tourism). This is especially true in small islands (29.3.3.1).

Most human-induced disturbances to coral reefs were local (e.g., coastal development, pollution, nutrient enrichment and overfishing) until the early 1980s when global and climate-related disturbances (ocean warming and acidification) began to occur. Temperature and seawater acidity are two of the most important environmental variables determining the distribution of coral reefs (Kleypas et al., 2001). As corals are centrally important as ecosystem engineers (Wild et al., 2011), the impacts on corals have led to widespread degradation of coral reefs.

A wide range of climatic and non-climatic stressors affect corals and coral reefs and negative impacts are already observed (5.4.2.4, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae (genus *Symbiodinium*), which live in the coral tissues and play a key role in supplying the coral host with energy and nutrients (Baker et al., 2008) (see 6.2.5 for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies, is the most widespread and conspicuous impact (Fig. 5X; see Sections, 5.4.2.4, 6.2.5, 25.6.2, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Elevated temperature along with ocean acidification reduces the calcification rate of corals (*high confidence*; 5.4.2.4), and may tip the calcium carbonate balance of reef frameworks towards dissolution (*medium evidence and agreement*; 5.4.2.4). These changes will erode fish habitats with cascading effects reaching fish community structure and associated fisheries (*robust evidence, high agreement*, 30.5).

Around 50% of all coral reefs have experienced medium-high to very high impact of human activities (30-50% to 50-70% degraded; Halpern et al., 2008), which has been a significant stressor for over 50 years in many cases. As a result, the abundance of reef building corals is in rapid decline (1 to 2% per year, 1997-2003) in many Pacific and SE Asian regions (Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and coral bleaching have led to a decline in coral cover on the Great Barrier Reef (about 51% between 1985 and 2012; De'ath et al., 2012).

One third of all coral species exhibit a high risk of extinction, based on recent patterns of decline and other factors such as reproductive strategy (Carpenter et al., 2008). Although less well documented, non-coral benthic invertebrates are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation coral reefs, including in a marine reserve (Jones et al., 2004). While many factors, such as overfishing and local pollution, are involved in the decline of coral reefs, climate change through its pervasive influence on sea temperature, ocean acidity, and storm strength plays a very significant role.

There is *robust evidence* and *high agreement* that coral reefs are one of the most vulnerable marine ecosystems (Chapters 5, 6, 25, and 30). Globally, more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011) even in the absence of climatic factors. Future impacts of climate stressors (ocean warming, acidification and sea level rise) will exacerbate the impacts of non-climatic stressors (*high agreement, robust evidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9–60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation under the RCP3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30–88%, 68% uncertainty range). If present day corals have residual capacity to acclimatize and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited*

agreement; Logan et al., sbm). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia & Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton et al. (2012) are already exploiting their coral reef fisheries in an unsustainable way (13.X.X).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4, 30.5).

Coral reefs make a modest contribution to the global domestic product but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent on average 5% of the GDP of South Pacific islands (Laurans et al., 2013). At the local scale, these two services provide at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are less effective in reducing coral loss from thermal stress (Selig et al., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012). Controlling the input of nutrients and sediment from land is an important complementary management strategy because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2012). There is also high confidence that, in the long term, limiting the amount of warming and acidity is central to ensuring the viability of coral reef systems and dependent communities (5.X.X and 30.5).

[INSERT FIGURE CR-1 HERE

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

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Box CC-RF. Impact of Climate-Change on Freshwater Ecosystems due to Altered River Flow Regimes
[Petra Döll (Germany), Stuart E. Bunn (Australia)]

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff *et al.*, 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e. changes to the frequency, magnitude, duration and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino *et al.*, 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario, 15% of the global land area may suffer, by the 2050s, from a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, like in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased run-off during winter months (Renofalt *et al.*, 2010).

[INSERT FIGURE RF-1 HERE
Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.]

Because biota are often adapted to a certain level of river flow variability, the larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke *et al.*, 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah *et al.*, 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5-7% of the global land area, mainly in semi-arid areas (Döll and Müller Schmied, 2012; see Chapter 3, Table 3-2).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme *et al.*, 2010). Eco-regions containing over 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme *et al.*, 2010).

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (chapter 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase,

when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C and 3.8°, respectively (van Vliet *et al.*, 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet *et al.*, 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction

Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult; observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean

acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a

locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

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Box CC-RC. Regional Climate Summary Figures

[Noah S. Diffenbaugh (USA), Daithi Stone (Canada), Filippo Giorgi (Italy), Bruce Hewitson (South Africa), Richard Jones (UK), Geert Jan van Oldenborg (Netherlands)]

The WGII regional climate summary figures draw on climate model simulations archived in Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). The CMIP5 simulations are also the basis for the figures presented in Annex I of the WGI contribution (*Atlas of Global and Regional Climate Projections*). The CMIP5 archive includes output from approximately three dozen climate models, including atmosphere-ocean general circulation models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, varies between the different CMIP5 experiments.

In contrast to CMIP3 (which used the IPCC SRES scenarios), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011) to simulate the climate response to possible changes in forcing over the 21st century. The WGI Atlas focuses on RCP4.5, with supplemental analysis of RCP2.6, RCP6.0, and RCP8.5. The WGII regional climate figures compare RCP4.5 and RCP8.5, using the same baseline, mid-21st-century, and late-21st-century time periods as the WGI Atlas (1986-2005, 2046-2065, 2081-2100). The RCPs exhibit overlapping likelihood of global warming in the mid-21st-century period (including median warming of 1.4˚C and 2.1˚C above the late-20th-century baseline in RCP4.5 and RCP8.5, respectively) (Rogelj et al. 2012), but divergent likelihood of global warming in the late-21st-century period (including median warming of 1.8˚C and 3.8˚C above the late-20st-century baseline in RCP4.5 and RCP8.5, respectively) (Rogelj et al. 2012). Given that real emissions have tracked on or above RCP8.5 in recent years (Peters et al. 2013), the regional climate figures are focused on the middle (RCP4.5) and upper end (RCP8.5) of the range of RCPs available in CMIP5.

The regional climate figures show the mean annual temperature and precipitation, categorizing differences in the CMIP5 simulation of the baseline and future periods into four classes. The classes are constructed based on the IPCC uncertainty guidance, which provides a quantitative basis for assigning likelihood statements (Mastrandrea et al. 2011). The classifications in the figures are constructed to parallel the 66-100% ("likely") and 90-100% ("very likely") probability ranges identified in the IPCC uncertainty guidance.

However, there are a number of plausible assignments of likelihood in a multi-model ensemble (e.g., (Knutti et al. 2010)). The classifications in the regional climate figures are based on two interpretations of likelihood reflected in the literature. The first interpretation is the likelihood that the climate in the future period is different than the climate in the baseline period (e.g., (Tebaldi et al. 2011). The regional climate figures use the percentage of models for which the simulated change exceeds two standard deviations of the simulated baseline variability as the measure of probability that the simulated future climate is statistically different than the simulated baseline climate. The second interpretation is the likelihood of the sign of change (e.g., (Christensen et al. 2007; Field et al. 2012). The regional climate figures use the percentage of models that exhibit the same sign of change as the measure of probability of increase or decrease in a given quantity.

The four classifications depicted in the regional climate figures are:

1) White indicates areas where less than 66% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability.
2) Gray indicates areas where greater than 66% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability, and less than 66% of the models agree on the sign of difference.
3) Colors with circles indicate areas where greater than 66% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability, and greater than 66% of the models agree on the sign of the difference. The color contour shows the magnitude of the multi-model mean difference between the future and baseline periods.
4) Colors without circles indicate areas where greater than 90% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability, and greater than 90% of the models agree on the sign of the difference. The color contour shows the magnitude of the multi-model mean difference between the future and baseline periods.

Only those models that have archived output from the historical, RCP4.5 and RCP8.5 experiments are included. For each of the included models, all realizations are used. For a given model, the mean and variability of each realization is first calculated for each period. The mean of the individual-realization mean and variability values are then calculated across the realizations of that model in each period, yielding model-mean mean and variability values derived from the timeseries of each realization (rather than from the mean of the timeseries). The difference between the model-mean in the future and baseline periods is then calculated for each model, and compared with each model's model-mean baseline variability. (Prior to analysis, each realization of each model is first interpolated to a common 1˚ geographical grid using linear interpolation.)

Because the regional climate figures quantify differences between 20-year periods, the measure of baseline variability is chosen to reflect the variability between 20-year periods in the baseline climate forcing. Given that the baseline period is selected as 1986-2005, the baseline variability is calculated as the standard deviation between the 20 20-year periods ending in the years 1986 through 2005 (1967-1986, 1968-1987, … , 1986-2005). Although the 20 20-year periods are not independent, they reflect the population of 20-year periods within the recent climate forcing regime, and a 20-year period that is more than two standard deviations removed is considered to be reflective of a different climate.

In addition to maps of the CMIP5 simulations, the regional climate figures also include maps of observed temperature and precipitation differences between the baseline period (1986-2005) and the early 20th century (1906-1925). The observational analyses use the CRU TS3.10.01 gridded station-based temperature and precipitation data (CRU 2012). On the observational panel, white indicates areas where the difference between the baseline and early-20th-century periods does not exceed two standard deviations of the early-20th-century variability. Colors indicate areas where the difference between the baseline and early-20th-century periods exceeds two standard deviations of the early-20th-century variability, with the color contours showing the magnitude of the difference. For the observational analyses, the early-20th-century variability is calculated as the standard deviation between the 20 20-year periods beginning in the years 1906 through 1925 (1906-1925, 1907-1926, … , 1925-1944).

[INSERT FIGURE RC-1 HERE
Figure RC-1: Change in annual temperature. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

[INSERT FIGURE RC-2 HERE
Figure RC-2: Change in annual precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a

change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

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Box CC-TC. Case Study Building Long Term Resilience from Tropical Cyclone Disasters
[Yoshiki Saito (Japan), Kathleen McInnes (Australia)]

Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves and storm surge, all of which can have major impacts on society and ecosystems. For example, Bangladesh and India account for 86% of mortality from tropical cyclones (Murray *et al.*, 2012), which is mainly due to the rarest and most severe storm categories (i.e. Categories 3, 4, and 5).

About 90 tropical cyclones occur globally each year (Seneviratne et al, 2012) although interannual variability is large. Changes in observing techniques particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities. Therefore, SREX concluded that there is *low confidence* that any observed long-term (i.e. 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne, *et al.*, 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is *likely* to increase. Regionally specific projections have *lower confidencelower confidence* (see WG1 Box 14.2).

Longer term impacts from tropical cyclones includes salinisation of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer term changes associated with climate change.

Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density in expanding urban areas (Nicholls *et al.*, 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray *et al.*, 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga *et al.*, 2003; Brakenridge *et al.*, 2012). The flooded areas were captured by a NASA MODIS image on 5 May 2008 (Figure TC-1).

[INSERT FIGURE TC-1 HERE
Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al.*, 2012).]

Murray *et al.* (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargs in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation (Murray et al, 2012). Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3,400 compared to over 138000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multi-storied cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. Birkmann and Teichman, (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use ($kWhr/m^3$) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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Box CC-VW. Active Role of Vegetation in Altering Water Flows Under Climate Change

[Richard Betts (UK), Dieter Gerten (Germany), Petra Döll (Germany)]

Terrestrial vegetation dynamics, carbon and water cycles are closely coupled, for example by the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis, and by feedbacks of land cover and land use change on water cycling.Numerous experimental studies have demonstrated that elevated atmospheric CO_2 concentration leads to reduced opening of stomatal apertures, associated with a decrease in leaf-level transpiration (de Boer *et al.*, 2011; Reddy *et al.*, 2011). This physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (iWUE) of plants, as less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) corroborate this finding, suggesting an increase in iWUE of mature trees by 20.5% between the 1970s and 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011). However, the physiological CO_2 effect is accompanied by structural changes to C3 plants (including all tree species), i.e. increased biomass production, spatial encroachment and, thus, higher transpiration, as confirmed by Free Air CO_2 Enrichment (FACE) techniques (Leakey *et al.*, 2009).

There are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.*, (2006) which suggested that physiological CO_2effects (lower transpiration) contributed to a supposed global increase in runoff seen in reconstructions by (Labat *et al.*, 2004). However, a more recent dataset (Dai *et al.*, 2009) showed different runoff trends in some areas. Detection of ecosystem influences on terrestrial water flows, hence, critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012).

A key influence on the significance of increased iWUE for large-scale transpiration is whether overall leaf area of primary vegetation has remained approximately constant (Gedney *et al.*, 2006) or has increased in some regions due to structural CO_2effects (as assumed in models by Piao *et al.*, 2007; Gerten *et al.*, 2008). While field-based results vary considerably between sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 200 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009), which is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 rise (McMahon *et al.*, 2010). The net impact of CO_2 on global-scale transpiration and runoff therefore remains poorly constrained.

Moreover, model results differ in terms of the importance of CO_2 effects for historical runoff relative to other drivers such as climate, land use change and irrigation water withdrawal. Other than Gedney *et al.*, (2006), Piao *et al.*, (2007) and Gerten *et al.*, (2008) found that CO_2 effects on global runoff were small relative to effects of precipitation, and that land use change (which often acts to decrease evapotranspiration and to increase runoff) was of second-most importance, as also supported by Sterling *et al.*, (2012) data and model analysis. By contrast, using a shorter time period and a smaller selection of river basins, Alkama *et al.*, 2011(2011) suggested that global effects of land use change on runoff have been negligible. Oliveira *et al.*, 2011(2011) furthermore point to the importance of changes in incident solar radiation and the mediating role of vegetation; their global simulations demonstrate, for example, that a higher diffuse radiation fraction during 1960–1990 increased evapotranspiration in the tropics by 3% due to increased photosynthesis from shaded leaves. Since the anthropogenic component of the precipitation and temperature contributions(i.e. of the radiative CO_2 effect) to runoff trends is not yet established, a full attribution of anthropogenic emissions of CO_2 (and other greenhouse gases)is still missing.

Analogously, there is uncertainty about how vegetation responses to future increases in CO_2 will modulate effects of climate change on the terrestrial water balance.21st-century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when CO_2-induced increases in iWUE are included in addition to climate change (Betts *et al.*, 2007; Murray *et al.*, 2012), potentially reducing an increase in water stress due to rising population or climate change (Wiltshire *et al.*, submitted) – although other models project a smaller response (Cao *et al.*, 2009). Direct effects of CO_2 on plants have been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012), depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the climate are accounted for. The model analysis by

Alkama *et al.*, (2010) suggests that although the physiological CO_2 effect will be the second-most important factor for 21st-centuryglobal runoff and although both physiological and structural effects will amplify compared to historic conditions, runoff changes will still primarily follow the projected climatic changes. Using a large ensemble of climate change projections, Konzmann *et al.*, (2013) put hydrological changes into an agricultural perspective and suggest that direct CO_2 effects on crops reduce their irrigation requirements (Fig. CC-VW-1). Thus, adverse climate change impacts on crop yields might be partly buffered as iWUE improves (Fader *et al.*, 2010), but only if proper management abates limitation of plant growth by nutrient availability or other factors. Lower transpiration under rising CO_2 may also affect future regional climate change itself (Boucher *et al.*, 2009) and may enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008).

Application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to changes in different climatic variables mediated by vegetation,with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). In a warmer climate with increased atmospheric CO_2 concentration, iWUE of plants increases and leaf area may either increase or decrease, and even though precipitation may slightly decrease, groundwater recharge may increase as a net effect of these interactions (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a location in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Future anthropogenic and climate-driven land cover and land use changes will also affect regional evapotranspiration, surface and subsurface water flows, with the direction and magnitude of these changes depending on the direction and intensity of the changes in vegetation coverage,as shown e.g. for a river basin in Iowa (Schilling *et al.*, 2008) or for the Elbe river basin (Conradt *et al.*, 2012).Removal of vegetation acting as source of atmospheric moisture can change regional water cycling and decrease potential crop yields by up to 17%in regions otherwise receiving this moisture in the form of precipitation (Bagley *et al.*, 2012).Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the climate system such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011) in that e.g. vegetation structure and composition can dynamically adapt to changing climatic and hydrologic conditions (Gerten *et al.*, 2007), it remains a challenge to disentangle the effects of future land cover changes on the water cycle.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).]

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Table TS.1: Observed impacts attributed to climate change with *medium* (*) or *high* (**) confidence. Impacts for physical, biological, and human systems are characterized across eight major world regions. For each observed impact, confidence in detection is equal to or greater than confidence in attribution. [Table 18-6, 18-7, 18-8, and 18-9]

REGION	Freshwater Resources & Systems	Terrestrial Ecosystems, Drought, & Wildfire	Coastal & Marine Systems	Human Systems
Africa	Retreat of tropical highland glaciers in East Africa* Lake surface warming & water column stratification increases in the Great Lakes & Lake Kariba** [13.2.1, 22.3.2, 22.5.1]	Tree density decreases in Sahel & semi-arid Morocco* Climate-driven range shifts of several southern plants & animals* Increased drought in the Sahel since 1970, partially wetter conditions since 1990* [22.2.2, 22.3.2]		Decline in fruit-bearing trees in Sahel*
Europe	Retreating glaciers in the Alps** Increase in rock slope failures in Western Alps** [18.3.1]	Earlier greening, earlier leaf emergence, & fruiting in temperate & boreal trees** Increased colonization of alien plant species in Europe* Earlier arrival of migratory birds in Europe since 1970* Increasing burnt forest areas during recent decades** [4.2.4, 4.4.1]	Poleward shifts in the distributions of zooplankton, fishes, seabirds, & benthic invertebrates, & conversion of polar into more temperate & temperate into more subtropical system characteristics in Northeast Atlantic** Phenology changes & retreat of colder water plankton to north in the Northeast Atlantic, with mean poleward movement of plankton reaching up to 200–250 km per decade from 1958–2005* Atlantic cod distribution shift due to warming, interacting with regime shift & regional changes in plankton phenology in North Sea.* Decreasing abundance of eelpout in Wadden Sea** [6.3.2, Table 6-8, Figure 6-16, 18.3.3, 30.5.1]	Stagnation of wheat yields in some countries in recent decades, due to warming and/or drought*
Asia	Permafrost degradation in Siberia, Central Asia, & Tibetan Plateau** Shrinking mountain glaciers across Asia.* Increased runoff in many rivers due to shrinking glaciers in the Himalayas & Central Asia** Surface water degradation in parts of Asia partially related to climate change* Earlier timing of maximum spring flood in Russian rivers** [Box 3-1, Box 3-2, 24.4.1, 28.2.1, WGI AR5 Chapter 4.3.2-4.3.3, 10.5.3]	Changes in plant phenology & growth in many parts of Asia, particularly in the north & east* Distribution shifts of many plant & animal species, particularly in the north of Asia, generally upwards in elevation or polewards* Advance of shrubs into the Siberian tundra* [4.2.1, Box 4-1, 24.4.2, 28.2.3]	Decline in coral reefs & large seaweeds in tropical Asian & Japanese waters** Shift from sardines to anchovies in Japanese Sea* [6.3.2, Figure 16-6, 24.4.3]	
Australasia	Significant decline in late-season snow depth at four alpine sites in Australia (1957-2002)*	Climate-related changes in genetics, growth distribution, & phenology of many species (e.g., earlier emergence of butterflies, change in plant flowering dates & bird breeding times, decline in body size of passerine birds)* [Table 25-3]	Mass bleaching of corals in the Great Barrier Reef, changes in coral calcification rates, & changes in coral disease dynamics** Multiple impacts of climate change on marine ecosystems from warming oceans, although other environmental changes may play a role. Examples are growth rate increases in fishes, intertidal-invertebrate range shifts, range shifts in near-shore fishes related to kelp decline, increasing abundance of northern marine species in Tasmania, recruitment declines of rock lobster & abalone, declines in growth rate & biomass of phytoplankton, southward expansion of some tropical seabirds in Australia** [6.3.2, Box 18-3, 25.6.2, Table 25-3]	Wine-grape maturation has advanced in recent decades, partly due to warming*

REGION	Freshwater Resources & Systems	Terrestrial Ecosystems, Drought, & Wildfire	Coastal & Marine Systems	Human Systems
North America	Primarily decreasing trends in amount of water stored in spring snowpack from 1960-2002** Observed shift to earlier peak flow in snow dominated rivers in Western North America** Runoff increases in the Midwestern & Northwestern US, decreases in Southern states* [26.2.2, WGI AR5 Chapter 2.6.2]	Species distribution shifts upward in elevation & northward in latitude across multiple taxa* Phenology changes* Increases in wildfire activity, including fire frequency & duration, length of fire season, & area burned* [26.4.1, 26.4.2, Box 26-2]	Northward range shifts of Northwest Atlantic fishes in response to warming since the 1960s, with some of the shifts being correlated with the Atlantic Multidecadal Oscillation* Earlier onset of Pink Salmon migration (Alaska), collapse of Sockeye Salmon spawning migration (Fraser River, BC), due to warming** Loss of biomass of midwater fishes off California Coast** [6.3.3, 6.6.3, Table 6-8, Figure 6-16]	Direct & indirect economic impacts of climate extremes on industry through reduced supply of raw material, the production process, the transportation of goods, & the demand for certain products* [26.8]
Central & South America	Retreat of tropical Andean glaciers in Venezuela, Colombia, Ecuador, Peru, & Bolivia (1950-2000) & glaciers & ice-fields in the extra tropical Andes** Changes in extreme flows in Amazon River* Changed discharge patterns in rivers in the Western Andes due to retreating glaciers & reduced snowpack; for major river basins in Colombia, decreased discharge during the last 30-40 years** Increased stream flow in sub-basins of the La Plata River, attributed to increasing precipitation, but also to trends in land-use changes that have reduced evapotranspiration** [27.2.1, 27.3.1]		Bleaching of coral reefs in the western Caribbean near the coast of Central America** [27.3.3]	Increase in frequency & extension of malaria* Increase in agricultural yields in Southeastern South America* [27.3.4, 27.3.7]
Polar Regions	Decreasing Arctic sea ice cover in summer & reduction in glacier ice volume, due to warming* Decreasing snow cover duration across the entire Arctic* Widespread permafrost degradation, especially in the southern Arctic** Rising winter minimum flows in most sectors of the Arctic due to enhanced groundwater input due to permafrost thawing* Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes being created in areas of formerly frozen peat** [28.2.1, 28.2.3, WGI AR5 Chapter 10.5.1]	Increase in shrub cover in tundra in North America & Eurasia.** Significant advance of Arctic tree-line in latitude & altitude, due to warming, although lower pace than expected due to insect outbreaks & land-use history. Changes in breeding area & population size of subarctic birds, due to warming & shrub encroachment in the tundra* Retreating snow-bed ecosystems & tussock tundra, due to prolonged thawing season & less precipitation in the form of snow.** Increasing occurrence of ice layers in the annual snow pack due to rain-on-snow events, affecting animal populations in the tundra* Increasing plant species in the West Antarctic Peninsula & nearby islands over the past 50 years** Increasing drought in high Arctic polar deserts** Increased frequency of wildfires in conifer forest at Arctic southern fringe, due to increasing summer temperature. Tundra wildfires are increasing in frequency in the Low Arctic, due to increasing summer air temperature & subsequent surface drought* [28.2.1, 28.2.3]	Sea ice loss negatively affecting many arctic & subarctic marine non-migratory mammals (walrus, seals, whales)** Reduced growth rate & body mass, lower survival & reproductive capacity of polar bears, linked to reduced off-shore range & sea-ice loss due to warming** Reduced reproductive success of Arctic seabirds, due to earlier sea-ice break-up* Reduced thickness of foraminifera shells due to acidification of Southern Ocean waters * Declines in Antarctic krill density in the Scotia Sea by ~30% since the 1980s, due to reduced winter sea ice extent & duration* Many Southern Ocean species of seals & seabirds, e.g., penguins & albatross, negatively responding to warmer conditions* Increased coastal erosion in Arctic, due to prolonged ice-free season at shore, increased exposure to wave activity, & degrading permafrost** [6.3.4, 28.2.2, 28.2.4, 28.2.5, 28.3.4]	Impact on livelihoods of Arctic indigenous peoples* [18.4.5, Box 18-5]
Small Islands		Tropical-bird population changes in Mauritius, due to changes in rainfall* [29.3.2]	Coral bleaching near many tropical small islands** [29.3.1]	

Table TS.2: Illustrative selection of some recent extreme impact events for which the role of climate has been assessed in the literature. The table shows confidence assessments as to whether the associated meteorological events made a substantial contribution to the impact event, as well as confidence assessments of a contribution of anthropogenic emissions to the meteorological event. The assessment of confidence in the findings is not necessarily a conclusion of the listed literature but rather results from assessment of the literature. Assessment of the role of anthropogenic emissions in the impact event requires a multi-step evaluation. [Table 18-4]

YEAR	REGION	EXTREME IMPACT EVENT		METEOROLOGICAL EVENT	
		Impact / damage	Confidence in contribution of extreme weather event to observed damage	Meteorological event	Confidence in contribution of anthropogenic emissions to extreme weather event
2003	Europe	excess death toll exceeding 70,000	*very high*	hottest summer in at least 500 years	*high*
2005	North Atlantic / USA	1,700 deaths and over 100 US$ Bn in damage	*very high*	record number of tropical storms, hurricanes, and category 5 hurricanes since 1970	*very low*
2006-2007	Europe	partial second flowering or extended flowering in 2006, early flowering in 2007	*high*	hottest record fall and winter in at least 500 years	*medium*
2010	Western Russia	burned area > 12,500km	*low*	hottest summer since 1500	*medium*
2011	Thailand	prolonged (up to 2 month) inundation of urban and industrialized areas, insured loss 8-11 US$ Bn, total loss ca. 45 US$ Bn	*very high*	wettest monsoon on record in middle and upper Chao Phraya Basin	*very low*
2010	Colombia	exceptionally heavy rainfall and floods, 4 M people affected, 7.8 US$ Bn total damage	*very high*	ENSO-related second and third highest SST in Caribbean on record in late 2010; second most active storm and hurricane season	*low*
2010	Pakistan	worst ever known floods in the region, 2000 people killed, 20 M affected, total loss 40 US$ Bn	*very high*	exceptionally high rainfall amounts over northern Pakistan with unusual atmospheric circulation patterns	*very low*
2011	Queensland, Australia	>200,000 people affected, >30,000 homes flooded, damages and cost to economy 2.5 – 10 US$ Bn	*very high*	2010 wettest year on record for Queensland, with extreme precipitation in January 2011 on saturated ground; record high Southern Oscillation Index in 2010	*low*

Table TS.3: Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.

Early warning systems for heat
EXPOSURE AND VULNERABILITY : Factors affecting exposure and vulnerability include age, pre-existing health status, level of outdoor activity, socio-economic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, urban heat island effects, and urban infrastructure. [11.7,SREX Table SPM.1]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: *Very likely* decrease in the overall number of cold days and nights and increase in the overall number of warm days and nights, on the global scale between 1951 and 2010. *Medium confidence* that the length of warm spells, including heat waves, has increased globally since 1950. Projected: *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global temperature increases, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 2.6.1, 12.4.3]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: *Medium confidence* in an increase in heat waves or warm spells over North America and Central America, Europe and the Mediterranean region, parts of Asia and Australia/New Zealand, and Southern Africa. Insufficient evidence for assessment or spatially varying trends in heat waves or warm spells for South America and most of Africa. Warming since 1901 generally greater in mid-to-high latitude regions. Projected: *Likely* that, under RCP8.5 in most regions, a 20-year maximum temperature event will at least double its frequency and in many regions occur every two years or annually, while 20-year minimum temperature events will become exceedingly rare by the end of the 21st century. *Likely* more frequent, longer, and/or more intense heat waves or warm spells in most regions of the world. [WGI AR5 2.4.3, 12.4.3; SREX Tables 3-2, 3-3]
DESCRIPTION: Heat-health early warning systems are instruments to prevent negative health impacts during heat waves. Weather forecasts are used to predict situations associated with increased mortality or morbidity. Essential and common components include identifying weather situations that adversely affect human health, monitoring weather forecasts, activating mechanisms for issuing warnings, targeting notifications of adaptation actions to the most vulnerable populations, and providing heat avoidance advice to the general population. Warning systems for heat waves have been used in Europe, the United States, Canada, and Australia. [11.7.3, 25.8.1, 26.9.1]
BROADER CONTEXT: •Heat warning systems appear effective in raising awareness of the risks associated with heat waves, although it is less certain whether this extends to behavioral changes. •Heat health warning systems can be combined with other elements of a health protection plan as has been done in France and Victoria, Australia, for example building capacity to support communities most at risk, supporting and funding health services, and distributing public health information. •In Africa, Asia, and elsewhere, early warning systems have been used to provide warning of and reduce a variety of risks, related to famine and food insecurity; cyclones, flooding, and other weather-related hazards; exposure to air pollution from fire; and vector-borne and food-borne disease outbreaks. [11.7.3, 25.8.1, 22.4.5, 11.7, , 15.3.2, box 21-3, 24.4.1, 24.4.6, Box 25-6]
Mangrove restoration to reduce flood risks and protect shorelines from storm surge
EXPOSURE AND VULNERABILITY : Loss of mangroves increases exposure of coastlines to storm surge, wave erosion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, are particularly vulnerable. [15.3.4, 29.7.2]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: *Likely* increase in extreme sea levels since 1970, mainly caused by rising mean sea level. *Low confidence* that any reported long-term changes in tropical cyclones are robust. Projected: By the end of the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in some basins. [WGI AR5 2.6.3, 3.7.5, 11.3.2, Box 14.2]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: Regional rates of sea level change can vary significantly from the global mean. Mean significant wave height *likely* increased since the mid-1980s over much of the mid-latitude North Atlantic, the North Pacific, and the Southern Ocean. For tropical cyclones observed over the satellite era, increases in the intensity of the strongest storms in the Atlantic appear robust. Projected: For all ocean basins, tropical cyclone frequency is projected to decline or remain the same, the mean lifetime maximum intensity of tropical cyclones is

projected to increase or remain the same, and cyclone-associated rainfall rates are projected to increase. In the North Atlantic and the eastern part of the North Pacific, the frequency of category 4/5 tropical cyclones is projected to increase.
Very likely increase in the occurrence of future extreme sea level and related coastal flooding events with increasing global mean sea level, but *low confidence* in region-specific projections in storminess and storm surges.
[WGI AR5 2.6.3, 3.4, 3.7, 13.7.2; Figures 3.6-3.8, 13.19; Box 14.2]

DESCRIPTION:
Mangrove restoration and rehabilitation has occurred in a number of locations (Vietnam, Myanmar, Samoa, and Brazil, for example) to reduce coastal flooding risks and protect shorelines from storm surge. In Vietnam, restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion.
[8.3.3.7, 2.3.4, 15.3.4, 27.3.3, 22.4.5]

BROADER CONTEXT:
•Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, wave damage, and erosion.
•Synergies with mitigation given that mangrove forests are sinks for carbon.
•Restoration and rehabilitation can help build local knowledge, capacity, and strategies to institutionalize climate change adaptation and resilience in local planning and development.
•Mangrove bioshields created from exotic species can detrimentally impact native ecosystems.
[8.4.2.4, Box 5.4, 29.7.2, 15.3.4]

Community-based adaptation and traditional practices in small island contexts

EXPOSURE AND VULNERABILITY:
With small land area, often low elevation coasts, and concentration of human communities and infrastructure in coastal zones with limited resettlement opportunities, small islands are particularly vulnerable to rising sea levels and impacts such as inundation, saltwater intrusion, and shoreline change. Island vulnerability to climate change may be related to the experience and perceptions of islanders to both climate and non-climate stressors.
[29.3.3, 29.6.1, 29.6.2]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Likely* increase in extreme sea levels since 1970, mainly caused by rising mean sea level.
Low confidence that any reported long-term changes in tropical cyclones are robust.
Likely increase in the number of heavy precipitation events in more regions than the number has decreased since 1950.
Projected: *Very likely* that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971-2010 for all RCP scenarios.
By the end of the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged.
Likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates.
More likely than not substantial increase in the frequency of the most intense tropical cyclones in some basins.
For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms.
[WGI AR5 2.6.2, 2.6.3, 3.7.5, 11.3.2, Box 14.2, 13.5.1, table 13.5, 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: Regional rates of sea level change can vary significantly from the global mean.
Mean significant wave height *likely* increased since the mid-1980s over much of the mid-latitude North Atlantic, the North Pacific, and the Southern Ocean.
For tropical cyclones observed over the satellite era, increases in the intensity of the strongest storms in the Atlantic appear robust.
Projected: For all ocean basins, tropical cyclone frequency is projected to decline or remain the same, the mean lifetime maximum intensity of tropical cyclones is projected to increase or remain the same, and cyclone-associated rainfall rates are projected to increase. In the North Atlantic and the eastern part of the North Pacific, the frequency of category 4/5 tropical cyclones is projected to increase.
Very likely increase in the occurrence of future extreme sea level and related coastal flooding events with increasing global mean sea level, but *low confidence* in region-specific projections in storminess and storm surges.
[WGI AR5 2.6.3, 3.4, 3.7, 13.7.2; Figures 3.6-3.8, 13.19; Box 14.2]

DESCRIPTION:
There is growing awareness of the role of traditional technologies and skills in adapting to climate change in small island contexts. In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after cyclone Ami, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Intensive participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices have been shown to be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa.
[29.6.2]

BROADER CONTEXT:
• Perceptions of self-efficacy in addressing climate stress can be an important pre-condition for anticipatory adaptation in islands. For example, individuals' belief in their own ability to cope with water scarcity based on past experience is a key driver of attitudes to and choice of adaptation strategy in Kiribati.
•The relevance of community-based adaptation principles to island communities, as a facilitating factor in adaptation planning and implementation, has been highlighted, for example with empowerment that helps people help themselves while addressing local priorities and building on local knowledge and capacity.
[29.6.2]

Farming practices in Africa, such as zai and integration of trees into annual cropping systems
EXPOSURE AND VULNERABILITY: Land degradation and soil infertility have negatively impacted yields in parts of Africa, such as in Zambia, Malawi, the highlands of Ethiopia, Burkina Faso, and the drylands of the Sahel. Soil erosion, soil compaction due to livestock trampling, and low soil water holding capacity reduce plant growth. [7.5.2, Table 9-6, Box 22-4]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: Increase in globally averaged near surface temperatures since 1900, with warming particularly marked since the 1970s. *Very likely* decrease in the overall number of cold days and nights and increase in the overall number of warm days and nights, on the global scale between 1951 and 2010. *Medium confidence* that the length of warm spells, including heat waves, has increased globally since 1950. *Medium confidence* in global precipitation change over land since 1950. *Likely* increase in the number of heavy precipitation events in more regions than the number has decreased since 1950. *Low confidence* in any observed large-scale trends in drought. Projected: For RCP 4.5, 6.0, and 8.5, global mean surface air temperatures are projected to at least *likely* exceed 2° C with respect to preindustrial by 2100. *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global temperature increases, for events defined as extremes on both daily and seasonal timescales. *Virtually certain* increase in global precipitation as global mean surface temperature increases. Regional to global-scale projections of soil moisture and drought remain relatively uncertain. For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 2.4, 2.5.1, 2.6.1, 2.6.2, 12.3.1, 12.4.1, 12.4.3, 12.4.5; Figures 2.28, 12.2, 12.5]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: Increase in frequency of warm days and nights in northern and southern part of continent and decrease in frequency of cold days and nights in southern part of continent. Overall increase in dryness and modest increases in rainfall over most of equatorial Africa and the Red Sea coast (*medium confidence*). Projected: *Likely* increase in warm days and decrease in cold days in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*). *Likely* more frequent and/or longer heat waves and warm spells in Africa (*high confidence*). [22.2.2; SREX Tables 3-2, 3-3]
DESCRIPTION: Zai uses small pits dug manually during the dry season, combined with contour stone bunds to slow runoff. Animal manure or compost is placed in each pit. The pits facilitate water infiltration and concentrate runoff water, and the applied organic matter improves soil nutrient status and attracts termites, which positively affect soil structure. The practice can also improve tree growth amid crop rows, and trees, especially nitrogen-fixing varieties, can be integrated as an independent strategy. Trees reduce crop exposure to wind and heavy rainfall and improve moisture retention and rainwater capture. Factors that have enabled farmer-managed natural regeneration include in southern Niger devolving tree ownership from the state to the farmer, as well as community-based efforts involving partnerships of farmers and NGOs. [7.5.2, Table 9-6, Box 22-4, 15.3.4]
BROADER CONTEXT: •Both techniques can improve yields, water retention, food security, and income generation, also reversing land degradation. •Tree growth, through production of fruit, animal fodder, or fuelwood, can expand livelihood options and allow diversification, thereby enhancing resilience. •Zai is a very labor-intensive technique, which can be expedited through use of animal-drawn implements. • Farmer-managed natural regeneration has been paired with other low-cost behavioral actions, for example in Ethiopia, aiming to reverse ecosystem degradation and promote reforestation with benefits for carbon sequestration. [7.5.2, Table 9-6, Box 22-4, 15.3.4, 17.4.1]
Adaptive approaches to flood defense in Europe
EXPOSURE AND VULNERABILITY : In some countries, a high percentage of the population is exposed to flooding. Exposed assets and infrastructure represent a substantial fraction of national GDPs. [Box 5-3]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: *Likely* increase in extreme sea levels since 1970, mainly caused by rising mean sea level. *Likely* increase in the number of heavy precipitation events in more regions than the number has decreased since 1950. Projected: *Very likely* that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971-2010 for all RCP scenarios. For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 2.6.2, 3.7.5, 12.4.5, 13.5.1, Table 13.5]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: Increased heavy wintertime precipitation since the 1950s in some areas of Northern Europe (*medium confidence*). Increased heavy precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*). Isostasy and decreasing sea level in Scandinavia. Projected: Overall precipitation increase in Northern Europe and decrease in Southern Europe (*medium confidence*). Increased extreme precipitation in Northern and Atlantic regions of Europe during all seasons, and in Central Europe except in summer (*high confidence*). Annual increases of intense precipitation days over the Mediterranean region. Storm activity over the North Atlantic *likely* to increase and extend farther downstream into Europe, and to decrease on both the north and south flanks, especially

over the Mediterranean (*medium confidence*).
Likely reduction in the occurrence of Northern Hemisphere extratropical storms, although the most intense storms reaching Europe *likely* to increase in strength. An increase in the North Atlantic Oscillation *likely* to increase the number of wintertime storms heading into Northern Europe and the average intensity of precipitation per storm.
[23.2.2; WGI AR5 Box 14.3; SREX Table 3-2]

DESCRIPTION:
Several governments have made ambitious efforts to address flood risk over the coming century. In the Netherlands, government recommendations include "soft" measures preserving land from development to accommodate increased river inundation; raising the level of lakes to ensure continuous freshwater supply; restoring natural estuary and tidal regimes; maintaining flood protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. The plan is estimated to cost €2.5 to 3.1 billion a year through 2050, 0.5% of the current Dutch annual GNP. The British government has also developed extensive adaptation plans to adjust and improve flood defenses for the protection of the Thames estuary and the city of London from future storm surges and river flooding. Pathways for different adaptation options and decisions depending on eventual sea level rise have been analyzed.
[Box 5-3, 23.7.1]

BROADER CONTEXT:
•The Dutch plan is considered a paradigm shift, addressing coastal protection by "working with nature" and providing "room for river." The concept of creating space for water and integrating water management approaches with goals of environmental protection is an essential component of integrated water management.
•The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise.
•The large infrastructure project of the Thames flood defense barrier involved public-private partnerships.
• In cities in Europe and elsewhere, the importance of having strong political leadership or government champions to drive the initial development of climate adaptation plans has been noted.
[Box 5.3, 23.7.1, 17.5.3, 8.5.3, 23.7.4, 23.7.2]

Index-based insurance for agriculture in Africa

EXPOSURE AND VULNERABILITY:
Susceptibility to food insecurity and depletion of farmers' productive assets following crop failure. Low prevalence of insurance due to absent or poorly developed insurance markets or to amount and timing of premium payments. The most marginalized and resource-poor especially may have limited ability to afford insurance premiums.
[Box 22-3, 13.3.2, 10.7.6]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Very likely* decrease in the overall number of cold days and nights and increase in the overall number of warm days and nights, on the global scale between 1951 and 2010.
Medium confidence that the length of warm spells, including heat waves, has increased globally since 1950.
Likely increase in the number of heavy precipitation events in more regions than the number has decreased since 1950.
Low confidence in any observed large-scale trends in drought.
Projected: *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global temperature increases, for events defined as extremes on both daily and seasonal timescales.
Regional to global-scale projections of soil moisture and drought remain relatively uncertain.
For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms.
[WGI AR5 2.6.1, 2.6.2, 12.4.3, 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: Increase in frequency of warm days and nights in northern and southern part of continent and decrease in frequency of cold days and nights in southern part of continent.
Overall increase in dryness and modest increases in rainfall over most of equatorial Africa and the Red Sea coast (*medium confidence*).
Projected: *Likely* increase in warm days and decrease in cold days in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*).
Likely more frequent and/or longer heat waves and warm spells in Africa (*high confidence*).
[22.2.2; SREX Tables 3-2, 3-3]

DESCRIPTION:
A recently introduced mechanism that has been piloted in a number of rural locations, including in Malawi, Ghana, and Ethiopia. When conditions reach a particular predetermined threshold where significant losses are likely to occur--weather conditions such as excessively high or low cumulative rainfall or temperature peaks affecting average crop yields or revenues--the insurance pays out. Where understanding of insurance is low, participation rates can be improved by using simulation games, as piloted in Ethiopia and Malawi, or by more conventional training methods.
[9.4.2, 15.2.4, 13.3.2, Box 22-3]

BROADER CONTEXT:
•Can be considered a low-regrets climate change adaptation option.
•The mechanism allows risk to be shared across communities, with costs spread over time, while overcoming obstacles to traditional agricultural and disaster insurance markets. It can be integrated with other strategies such as micro-finance and social protection programs.
•Risk-based premiums foster risk awareness and risk reduction by providing financial incentives to policyholders to reduce their risk profile.
•Challenges can be associated with limited availability of accurate weather data, difficulties in establishing which weather conditions cause losses, and varying weather conditions between adjacent areas and meteorological stations. Basis risk (i.e., farmers suffer damage but no payout is triggered based on weather data) can promote distrust. There can also be difficulty in scaling up successful pilot schemes.
•Insurance for work programs can enable cash-poor farmers to work for insurance premiums by engaging in community-identified disaster risk reduction projects.
[15.2.4, 13.3.2, Box 22-3, 15.2.2, Box 25-7, 10.7.6, 10.7.5]

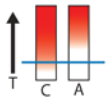
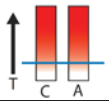
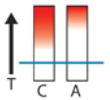
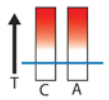
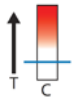
Relocation of agricultural industries in Australia
EXPOSURE AND VULNERABILITY : Crops sensitive to changing patterns of rainfall, water availability, and temperature. [7.5.2]
CLIMATE INFORMATION AT THE GLOBAL SCALE: Observed: Increase in globally averaged near surface temperatures since 1900, with warming particularly marked since the 1970s. *Very likely* decrease in the overall number of cold days and nights and increase in the overall number of warm days and nights, on the global scale between 1951 and 2010. *Medium confidence* that the length of warm spells, including heat waves, has increased globally since 1950. *Medium confidence* in global precipitation change over land since 1950. *Likely* increase in the number of heavy precipitation events in more regions than the number has decreased since 1950. *Low confidence* in any observed large-scale trends in drought. Projected: For RCP 4.5, 6.0, and 8.5, global mean surface air temperatures are projected to at least *likely* exceed 2° C with respect to preindustrial by 2100. *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global temperature increases, for events defined as extremes on both daily and seasonal timescales. *Virtually certain* increase in global precipitation as global mean surface temperature increases. Regional to global-scale projections of soil moisture and drought remain relatively uncertain. For short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 2.4, 2.5.1, figure 2.28, 2.6.1, 2.6.2, 12.3.1, 12.4.1, figure 12.2, figure 12.5, 12.4.3, 12.4.5]
CLIMATE INFORMATION AT THE REGIONAL SCALE: Observed: Mean temperature increase of 0.9°C per decade over Australia since 1911 (*very high confidence*). Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand (*high confidence*). Late autumn/winter decreases in precipitation in Southwestern Australia since the 1970s and Southeastern Australia since the mid-1990s, and annual increases in precipitation in Northwestern Australia since the 1950s (*very high confidence*). Significant increases in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). Projected: Further warming of Australasia this century *virtually certain*, greatest over inland areas and least in coastal areas. Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). Annual decline in precipitation over southwestern Australia (*high confidence*) and in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). Increase in intensity of rare daily rainfall extremes (*high confidence*) and of annual daily extremes (*medium confidence*) in Australia and New Zealand. Drought occurrence to increase in Southern Australia (*high confidence*). Snow depth and snow area to decline in Australia (*very high confidence*). Freshwater resources projected to decline in the highly populated southeast and the far southwest of Australia. [25.5.1, Table 25-1]
DESCRIPTION: Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use in situ in response to recent climate change or perceptions of future change. There have been new investments in grapes in Tasmania and switching from grazing to cropping in South Australia. Adaptive movement of crops has also occurred elsewhere, such as in China. [7.5.2, Table 9-6, 25.7.2, Box 25-5]
BROADER CONTEXT: •Considered transformational adaptation in response to impacts of climate change. •Positive or negative implications for communities in origin and destination regions, with substantial changes required in transport chains, inputs, management, or growing contracts. •Some decisions run across scales and include many stakeholders, with comprehensive regional assessments across enterprises and economic and resource outcomes needed. [7.5.2, 25.7.2, Box 25-5]

Table TS.4: Entry points, strategies, measures, and options for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples given can be relevant to more than one category.

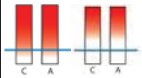
Entry Point	Category			Examples	Chapter Reference(s)
Vulnerability reduction through development and planning	Forms of sectoral integration	Human development	Specific measures	Low regrets options to reduce structural inequalities: improved access to education, nutrition, health facilities, energy, safe settlement structures, social support structures; reduced gender inequality and marginalization in other forms.	13.1.2, 13.3.1, 13.4.1, 13.4.2, 22.3.1
		Poverty alleviation		Insurance schemes, social protection programs, disaster risk reduction. Improved access to and control of local resources, land tenure, and storage facilities. Low regrets options to reduce structural inequalities.	13.1.2, 13.3.1, 13.3.2, 13.4.1
		Livelihood security		Income and asset diversification. Improved infrastructure. Access to technology and decision-making fora, enhanced agency.	13.1.1, 13.3.1, 13.4.1
		Disaster risk reduction and management		Early warning systems.	11.7.3, 22.4.5, 26.9.1
		Ecosystem management		Maintaining wetlands and urban green spaces, coastal afforestation.	8.3.3, Box 8.1, 15.3.1, Box CC-EA
		Spatial or land-use planning		Provisioning of adequate housing, infrastructure, and services. Managing development in flood prone and other high risk areas.	8.1.4, 8.4.3, 8.5.3
Adaptation	Structural/ concrete	Engineered	Specific options	Sea walls, water storage, improved drainage, beach nourishment, flood shelters. Improved infrastructure.	14.3.1, Table 14-2
		Technological		New crop and animal varieties, efficient irrigation and water use, hazard mapping and monitoring, early warning systems, home insulation.	14.3.1, Table 14-2
		Ecosystem-based		Wetland reestablishment, reestablishment of floodplains, bushfire fuel-reduction actions.	14.3.1, Table 14-2
		Services		Social safety nets, food banks, vaccination programs, municipal services.	14.3.1, Table 14-2
	Institutional	Economic	Specific options	Financial incentives, insurance and other risk spreading.	13.3.2, 14.3.2, Table 14-2
		Laws and regulations		Land zoning laws, building standards, easements.	14.3.2, Table 14-2
		Government policies and programs		National and local adaptation plans, urban upgrading programs, municipal water conservation programs, disaster planning and preparedness.	14.3.2, Table 14-2
	Social	Educational	Specific options	Awareness raising, extension services.	14.3.3, Table 14.2
		Informational		Hazard mapping and monitoring, early warning, community support groups.	14.3.3, Table 14-2
		Behavioral		Household preparation, evacuation planning, retreat and migration, water conservation, storm drain clearance.	14.3.3, Table 14-2
Transformation	Spheres of change	Practical	Specific strategies	Social and technical innovations, behavioral shifts, or institutional and managerial changes that produce measurable outcomes.	20.5.2
		Political		Changes in the political, social, cultural and ecological systems or structures that currently contribute to risk and vulnerability or impede practical transformations.	20.5.2
		Personal		Changes in individual and collective assumptions, beliefs, values, and worldviews that influence climate change responses.	20.5.2
Mitigation	See WGIII AR5.				

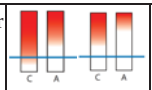
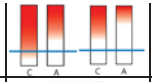
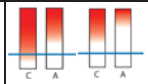
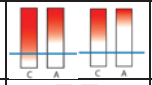
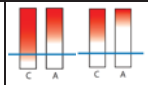
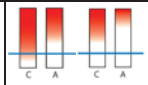
Table TS.5: Examples of risks that increase with increasing level of climate change. Examples of potential positive impacts are also given. Risks increasing moderately or severely from now until the 2040s, which can be considered an era of climate responsibility, are described, in addition to risks increasing from ~2050 through the end of the 21st century, which can be considered to represent an era of climate options. For risks increasing in both the era of climate responsibility and the era of climate options, the potential for proactive adaptation to reduce the risks is characterized as low or high, with detail provided on adaptation issues and prospects. Risks increasing in the era of climate options can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options. Increasing risks in the era of climate responsibility are generally difficult to reduce substantially through mitigation, even with globally effective mitigation. They can be managed through vulnerability reduction, adaptation, and transformations that promote climate-resilient development pathways.

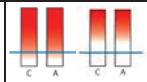
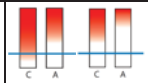
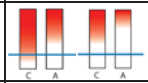
---------- LEGEND ----------

ERA & ADAPTATION POTENTIAL	Risk for current (C) and hypothetical fully adapted (A) state. Color scheme depicts the additional risk due to climate change. White to red indicates lower and higher levels of risk, respectively. The vertical axis of each bar represents the level of climate change (T). The horizontal blue line indicates the level of climate change at the end of the era of climate responsibility.	
	A risk increasing moderately as early as the era of climate responsibility (now through the 2040s), which can be reduced substantially with proactive adaptation.	 A risk increasing moderately as early as the era of climate responsibility (now through the 2040s), which will be difficult to reduce substantially even with proactive adaptation.
	A risk increasing moderately or severely during the era of climate options (~2050 through the end of the 21st century), which can be reduced substantially with proactive adaptation. The risk can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options.	 A risk increasing moderately or severely during the era of climate options (~2050 through the end of the 21st century), which will be difficult to reduce substantially even with proactive adaptation. The risk can generally be reduced through globally effective mitigation occurring during the era of climate responsibility and the era of climate options.
	A risk increasing moderately as early as the era of climate responsibility (now through the 2040s), for which potential for risk reduction via proactive adaptation was not assessed.	 A risk increasing moderately or severely during the era of climate options (~2050 through the end of the 21st century), for which potential for risk reduction via proactive adaptation was not assessed.

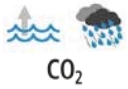
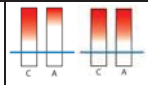
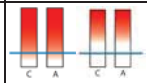
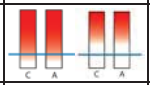
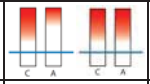
CLIMATE DRIVERS	Where particular climate driver(s) are especially relevant for an assessed risk, they are indicated via the symbols below.							
	Average temperature		Extreme temperature		Precipitation		Extreme precipitation
CO_2	CO_2 concentration & ocean acidification		Damaging cyclone		Snow cover		Sea level

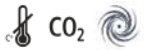
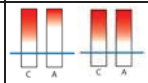
REGION	CROSS-SECTORAL RISKS			
	Risk	Era & Adaptation Potential	Adaptation Issues/Prospects	Chap. Ref.
Global	Stringent mitigation scenarios can potentially avoid one half of the aggregate economic impacts that would otherwise accrue by 2100, and between 20-60% of the physical impacts, depending on sector and region.			19.7.1, 19.7.2
	Key risks associated with global temperature rise in excess of 4°C relative to preindustrial levels include exceedance of human physiological limits in some locations and nonlinear earth system responses (*high confidence*).			19.5.1, 19.6.3, Box TS.6
	Warming of up to 2°C above 1990-2000 levels would result in significant impacts on many unique and vulnerable systems, and would likely increase the endangered status of many threatened species (*high confidence*), with increasing adverse impacts and increasing risk of extinctions (and increasing confidence in this conclusion) at higher temperatures.		Unique human and natural systems tend to have very limited adaptive capacity. Climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C over preindustrial levels were exceeded (*high confidence*).	19.6.3

	Since AR4, the assessment of overall risk from extreme events due to climate change has not changed significantly, but there is higher confidence in the attribution of some types of extreme events to human activity and in the assessment of the risk from extreme events in the coming decades.			There is a new appreciation for the importance of exposure and vulnerability, in both developed and developing countries, in assessing risk associated with extreme events.	19.6.1, 19.6.3
REGION	**FRESHWATER RESOURCES AND SYSTEMS**				
	Risk	**Climate Driver(s)**	**Era & Adaptation Potential**	**Adaptation Issues/Prospects**	**Chap. Ref.**
Global	Hydrological impacts of climate change increase with increasing greenhouse-gas emissions (*high agreement, robust evidence*).			A low-emissions pathway reduces damage costs and costs of adaptation.	Table 3-2, 3.4, 3.5, 3.6.5
	Glaciers will continue to lose mass, with meltwater yields from stored glacier ice eventually diminishing as the glaciers shrink (*high agreement, robust evidence*).				3.4.4
Europe	Climate change is *likely* to further increase coastal and river flood risk and, if unabated, will substantially increase flood damages (monetary losses and people affected).			Adaptation can prevent most of the projected damages (*high confidence*).	23.3.1, 23.5.1, 23.7.1, 23.8.3
Asia	Shrinking of glaciers in Central Asia and the Himalayas is projected to affect water resources in downstream river catchments. Population growth and increasing demand arising from higher standards of living could worsen water security in many parts of Asia and affect many people in the future.			Water saving technologies and changing to drought tolerant crops have been found to be successful adaptation options in the region.	24.4.1, 24.9.3
Australasia	Systematic constraints on water resource use in southern Australia, driven by rising temperatures and reduced cool-season rainfall (*high confidence*).			Integrated responses encompassing management of supply, recycling, water conservation, and increased efficiency across all sectors are available but face implementation constraints.	25.2, 25.5.1, Box 25-2
	Increased frequency and intensity of flood damage to settlements and infrastructure in Australia and New Zealand, driven by increasing extreme rainfall although the amount of change remains uncertain (*high confidence*).			In many locations, continued reliance on increased protection alone would become progressively less feasible.	Table 25-1, 25.4.2, 25.10.3, Box 25-8
North America	Throughout North America, it is *very likely* that the 21st century will witness decreases in water quality, and increases in flooding and droughts under climate change, with these impacts exacerbated by other anthropogenic drivers. It will also witness decreases in water supplies for urban areas and irrigation in some areas of North America, with confounding effects of development.				26.3, 26.8
Central and South America	For regions already vulnerable in terms of water supply, such as the semi-arid zones in Chile-Argentina, North Eastern Brazil, and Central America and the tropical Andes, glacier retreat and a reduction in water availability due to expected precipitation reduction and increased evapotranspiration demands are expected, affecting water supply for large cities, small communities, hydropower generation, and the agriculture sector.			Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability.	27.3.1, 27.6.1
REGION	**TERRESTRIAL ECOSYSTEMS, DROUGHT, & WILDFIRE**				
	Risk	**Climate Driver(s)**	**Era & Adaptation Potential**	**Adaptation Issues/Prospects**	**Chap. Ref.**
Global	Drying of soils is projected in most dry regions (*medium confidence*).				3.4.9, 3.5, WGI AR5 12.4.5
	For freshwater ecosystems (*high confidence*) and terrestrial ecosystems (*medium confidence*), direct human impacts such as land-use change, pollution, and water resource development will continue to dominate threats to ecosystems, with climate change becoming an increasing additional stress through the century, especially for high-warming scenarios such as RCP 6.0 and 8.5.			Management actions can reduce, but not eliminate, exposure to climate-driven ecosystem impacts, and can increase ecosystem adaptability (*high confidence*).	Box CC-RF, 4.3.3, 4.4.1, 4.4.3

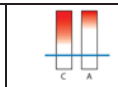
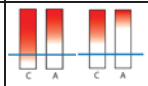
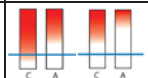
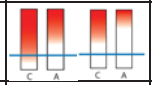
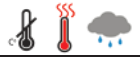
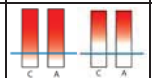
	For high altitude and latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP 2.6 will lead to major changes in species distributions and ecosystem function.				4.3.2, 4.3.3, 4.4.1
	Even for mid-range rates of climate change (i.e., RCP 4.5 and 6.0), many species will be unable to move fast enough to track suitable climates (*medium confidence*). Era of relevance depends on species and habitat type.			Low migration capacity and large flat areas pose the most serious problems for tracking climate. Capacity for natural adaptation is substantial but, for many ecosystems and species, insufficient to cope with the rate and magnitude of climate change projected under RCP 6.0 or 8.5.	4.3.2, 4.3.3, 4.4.1, 4.4.3
	Large magnitudes of climate change will negatively impact species with populations primarily restricted to protected areas, mountaintops, or mountain streams, even those that potentially migrate fast enough to track suitable climates (*high confidence*).			Capacity for ecosystems to adapt to climate change can be increased by, for example, assisted translocation.	4.3.2, 4.3.4, 4.4.1, 4.4.3
	Increased extinction risk for a substantial fraction of species during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, over-exploitation, and invasive species (*very high confidence*).			Capacity for ecosystems to adapt to climate change can be increased by reducing other stresses; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; and manipulation of disturbance regimes.	4.3.2, 4.4.1, 4.4.3
Africa	Many fragile terrestrial and aquatic ecosystems are implicitly or explicitly water dependent. Impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical socio-political and economic footprint (*high confidence*).				22.3.2, 22.3.3
Europe	Changes in habitats and species will result in local extinction (*high confidence*) and continental scale shifts (*low/medium confidence*). Increasing local loss of native species and extinction of species across most sub-regions of Europe by 2050 (medium emissions) with economic development and land-use change. Introduction and expansion of invasive species, especially those with high migration rates, from outside Europe will increase with climate change (*medium confidence*).				23.4.4, 23.6.4, 23.6.5, 23.10, Table 23.2
	Climate change will increase damage to forests from pests and diseases in all sub-regions (*high confidence*), from wildfires in Southern Europe (*high confidence*), and from storms (*low confidence*).				23.4.4
Asia	Terrestrial systems are under increasing pressure from both climatic and non-climatic drivers. The projected changes in climate will impact vegetation and increase permafrost degradation during the 21st century (*high confidence*). The largest changes are expected in cold northern and high-altitude areas, where boreal and subalpine trees will *likely* invade treeless arctic and alpine vegetation, and evergreen conifers will *likely* invade deciduous larch forest.				24.2.2, 24.4.2, 24.4.3, 24.9.3
Australasia	Loss of montane ecosystems and some endemic species in Australia, driven by rising temperatures, increased fire risk and drying trends (*high confidence*).			Fragmentation of landscapes, limited dispersal and evolutionary capacity limit adaptation options.	25.6.1
	Projected changes in climate and increasing atmospheric CO_2 have the potential to benefit forest growth in cooler regions except where soil nutrients or rainfall are limiting (*high confidence*).				25.7.1, 25.7.2
	Increased damages to ecosystems and settlements, economic losses, and risks to human life from wildfires in most of southern Australia and many parts of New Zealand, driven by drying trends and rising temperatures (*high confidence*).			Building codes, design standards, local planning mechanisms, and public education can assist with adaptation and are being implemented in regions that have experienced major events.	25.2, Table 25-1, 25.6.1, 25.7.1, Box 25-6
North America	A global increase of 2°C would have widespread adverse impacts on many ecosystems, *likely* reducing biodiversity and ecosystem services (*high confidence*).				26.4

Central and South America	Continued climate change together with land use change and fire activity could cause much of the Amazon forest to transform abruptly to more open, dry-adapted ecosystems, and in doing so, put a large stock of biodiversity at elevated risk and create a large new net greenhouse gas source to the atmosphere (*low confidence*). The combination of climate change and land-use change in the Amazon will cause accelerated drying and drought frequency in the region (*medium confidence*), and there is *low confidence* that these Amazon changes will affect rainfall in agricultural regions elsewhere on the planet.			Rigorously applied adaptation measures could lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*).	4.2.2, 4.2.4, 4.3.3, Box 4-3, Box 4-4, Figure 4-10
Polar Regions	Continued climate change could push the boreal-arctic system across a tipping point in this century and cause an abrupt transformation of the ecology and albedo of this region, as well as the release of greenhouse gases from thawing permafrost and burning forests (*low confidence*).			Adaption measures will be unable to prevent substantial change in the boreal-arctic system (*high confidence*).	4.2.2, 4.2.4, 4.3.3, Box 4-3, Box 4-4, Figure 4-10

REGION	COASTAL & MARINE SYSTEMS Risk	Climate Driver(s)	Era & Adaptation Potential	Adaptation Issues/Prospects	Chap. Ref.
Global	Under medium socio-economic development assumptions, the expected direct global annual cost of coastal flooding (adaptation and residual damage costs) may reach 300 US$ billion per year in 2100 without adaptation and 90 US$ billion per year with adaptation under a 1.26 m sea-level rise scenario.				5.4.3, 5.5.3
	While developed countries are expected to be able to adapt to even high levels of sea-level rise, small island states and some low-lying developing countries are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of GDP (*high agreement*). Developing countries and small island states within the tropics relying on coastal tourism are impacted not only directly by future sea-level rise and associated extremes but also by the impacts of coral bleaching and ocean acidification and reductions in tourist flows from other regions (*very high confidence*).				5.4.3, 5.5.3
	Physical effects of climate change on marine ecosystems may act, under some circumstances, as an additional pressure that cannot be ameliorated by local conservation measures or a reduction in human activities like fishing (*high confidence*).				6.4
	Some warm water corals and their reefs will continue to respond to warming with species replacement, bleaching, and decreased coral cover. The projected degradation of some marine ecosystems such as coral reefs and Mediterranean intertidal communities is *very likely* to pose substantial challenges for coastal societies where livelihoods and food security may depend on ecosystem health.			Genetic adaptation may occur; the capacity to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*).	6.2, 6.3, 6.5.2, 30.4, 30.5.3, 30.5.6, Box CC-CR
	Through species gains and losses correlated with warming, the diversity of animals and plants will increase at mid and high latitudes (*high confidence*) and fall at tropical latitudes (*low confidence*), leading to a large-scale redistribution of global catch potential for fishes and invertebrates (*medium confidence*). Animal displacements are projected to lead to a 30–70% increase in the fisheries yield of high-latitude regions but a drop of 40–60% in the tropics by 2055 relative to 2005 under the SRES A1B scenario (*medium confidence* for the general trend of shifting fisheries yields, *low confidence* for the magnitude of change).				6.2.5, 6.3.2, 6.4, 6.5, 6.5.2
	Changes in ocean mixing, nutrient levels, and primary productivity are *very likely* to have positive consequences for some fisheries and negative ones for others through the de-oxygenation of deep water environments and associated spread of hypoxic zones (*medium agreement, medium evidence*).				30.5, 6.2, 6.3, 6.5
	Changes to surface winds, sea level, wave height, and storm intensity will increase the risks associated with coastal and ocean based industries such as shipping, oil, gas, and mineral extraction (*medium agreement, medium evidence*).				30.6, 6.5
Africa	Impacts of climate change, mainly through sea level rise, combined with other extreme events (such as high tide levels and high storm swells) have the potential to threaten coastal zones, particularly coastal towns (*high confidence*).				22.3.2, 22.3.4, 22.3.7
Europe	Costs of adapting dwellings or upgrading coast defence will increase under all scenarios (*high confidence*).				23.3.2, 23.6.5, 23.7.3

	Climate change will not decrease net fisheries economic turnover in some parts of Europe (e.g., Bay of Biscay) (*low confidence*) due to introduction of new (high temperature tolerant) species. Climate change will not entail relocation of fishing fleets (*high confidence*).				23.4.6
Asia	In the Asian Arctic, rising sea levels will interact with projected changes in permafrost and the length of the ice-free season to cause increased rates of coastal erosion (*high agreement, medium evidence*).				24.4.3
Australasia	Significant change in community structure of coral reef systems in Australia, driven by increasing sea-surface temperatures and ocean acidification (*high confidence*).			The natural ability of reefs to adapt to projected changes is limited.	Box CC-CR, 25.6.2, 30.5
	Widespread damages to coastal infrastructure and low-lying ecosystems in Australia and New Zealand if sea level rise exceeds 1m (*high confidence*). Risks from sea level rise *very likely* continue to increase beyond 2100 even if temperatures are stabilized.			Managed retreat is a long-term adaptation strategy for human systems but options for some natural ecosystems are limited due to the rapidity of change and lack of suitable space for inland migration.	WGI AR5 13.ES; Box 25-1, Table 25-1, 25.4.2, 25.6.1-2
Polar Regions	Shifts in the timing of seasonal biomass production could disrupt matched phenologies in food webs, leading to decreased abundance of high latitude marine organisms (*medium confidence*).				28.2.2, 28.3.2

REGION	HUMAN SYSTEMS Risk	Climate Driver(s)	Era & Adaptation Potential	Adaptation Issues/Prospects	Chap. Ref.
Global	Global arable area is *likely* to increase from 2007 to 2050 (*high agreement, medium evidence*), with projected increases over this period of between 9% and 25% (*medium agreement, medium evidence*). From the mid-21st century onwards, the human food system at scales from the local to global and particularly in low-latitude lands will be seriously and negatively affected by projected climate change (*high agreement, robust evidence*). For 4-6 °C global mean temperature above pre-industrial levels, global risks to food production and security may become very severe (*high agreement, medium evidence*).			Adaptation possibilities for food systems vary widely in effectiveness. Adaptation will increase in effectiveness up to ca. 3°C local mean warming above pre-industrial, after which the net benefits no longer increase (*medium confidence*).	7.1, 7.2, 7.3, 7.4, 7.5, 7.6, Figures 7-5, 7-9
	Without adaptation, moderate warming of up to 2°C local temperatures is expected to reduce yields on average for the major cereals (wheat, rice, and maize) in temperate regions, although many individual locations may benefit (*medium confidence*). There is confirmation that even modest warming up to 2°C will decrease yields in low-latitude tropical regions (*medium agreement, robust evidence*).			Benefits of adaptation are greater for wheat, rice, and maize in temperate rather than tropical regions.	7.1, 7.3.2, 7.4-6, Figs 7-5, 7-6, 7-7, 7-9
	Yield reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. From the 2070s, all positive yield changes are in temperate regions, suggesting yield reductions in the tropics are *very likely* by this time and substantial, particularly for wheat (*high agreement, robust evidence*).				7.4, Figures 7-5, 7-6, and 7-7
	Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security while affecting rural households depending on whether they are net buyers or net sellers of food (*medium* to *high confidence*).			Deepening agricultural markets through reforming trade and institutional efforts to improve the predictability and reliability of the world trading system, as well as investing in supply capacity of small-scale farms in developing countries, could help reduce market volatility and manage food supply shortages (*medium agreement*).	9.3.3
	In the next few decades, climate change will increase incidence of injury, disease, and death due to more intense heat waves, storms, floods, and fires; increase risk of under-nutrition in some developing regions; reduce work capacity and labor productivity in vulnerable populations; increase risks of food- and water-borne diseases and vector-borne infections; and modestly improve health outcomes in some areas due to lower impacts of cold, shifts in food production, and reduction of disease-carrying vectors. Positive health effects will be out-weighed, world-wide, by the magnitude and severity of negative impacts.			Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development, particularly among the poorest and least healthy groups.	11.4, 11.5, 11.6, 11.7

	For RCP 8.5 by 2100, limits to adaptation for health impacts may be exceeded in many areas of the world (*high confidence*), related to sea level rise, storms, loss of agricultural productivity, and daily temperature/humidity conditions that exceed coping mechanisms.				11.8
	Climate change threatens human security, because it a) undermines livelihoods, b) compromises culture and identity, c) increases migration that people would rather have avoided, and d) undermines the ability of states to provide the conditions necessary for human security (*high agreement, robust evidence*). Increases in the rate and magnitude of climate change increase the risk to human security by exacerbating negative feedbacks between cultural processes, migration, and violent conflict.			Human security breakdowns almost never have single causes, but instead emerge from the interaction of multiple factors. For populations already socially marginalized and resource dependent with limited capital assets, human security will be progressively undermined as the climate changes.	12.1.2, 12.2, 12.7
Africa	Spatial convergence of impacts in different sectors creates impact "hotspots" involving new interactions, for example, in Sub-Saharan Africa where global warming at the high end of the range projected for this century, i.e., more than 4°C above preindustrial levels, would be especially disruptive, resulting in high risk of reduced extent of croplands, reduced length of the growing season, increased hunger, and increased malaria transmission.				19.3.2
	Temperature rise and a reduction in growing season length by mid-century are expected to significantly reduce crop productivity with strong adverse effects on food security. New challenges to food security are emerging as a result of strong urbanization trends on the continent and increasingly globalized food chains, which require better understanding of the multi-stressor context of food and livelihood security.				22.3.4
	Climate change is expected to increase the burden of a wider range of health outcomes (*medium confidence*).				22.3.5
Europe	Increasing heat wave mortality across most sub-regions of Europe by 2050 (medium emissions) with economic development and land-use change. Particularly in Southern Europe, increased frequency and intensity of heat waves (*high confidence*) will have adverse implications for health, agriculture, energy production, transport, tourism, labour productivity, and built environment (*medium confidence*).				23.2.2, 23.5.1, Tables 23-4, 23-5
	Climate warming will decrease space heating demand and increase cooling demand (*high confidence*), with income growth driving the largest part of this increase from 2000-2050 (especially in eastern regions) (*medium confidence*). Climate change will increase problems associated with overheating in domestic housing.			Energy efficient buildings and cooling systems as well as demand-side management will reduce future energy demands.	23.3.2, 23.3.4
	Climate change will increase yields in Northern Europe (*medium confidence*) but decrease cereal yields in Southern Europe (*high confidence*).				23.4.1, 23.4.2, 23.5.1
	Climate change will increase irrigation needs (*high confidence*), but future irrigation will be constrained by reduced runoff, demand from other sectors, and economic costs. By 2050s, irrigation will not be sufficient to prevent damage from heat waves to crops (*medium confidence*).				23.4.1, 23.4.3, 23.7.2
	Climate change will decrease hydropower production from reductions in rainfall in all sub-regions except Scandinavia (*high confidence*). Climate change will inhibit thermal power production during summer (*medium confidence*).			Plant modifications and operational changes can reduce adverse impacts.	23.3.4
	No significant impacts are projected before 2050 in winter or summer tourism except for ski tourism in low- and mid-altitude sites and under limited adaptation (*medium confidence*). After 2050, tourism activity will decrease in southern Europe (*low confidence*) and increase in northern/continental Europe (*medium confidence*).				23.3.6
	Increasing damage of cultural buildings and loss of cultural landscapes across most sub-regions by 2050 (medium emissions). Climate change and sea level rise will damage cultural heritage and iconic places such as Venice (*medium confidence*), and some cultural landscapes will be lost forever (*low/medium confidence*).				23.5.4, Table 23-5
Asia	The impacts of climate change on food production and food security will vary by region with many regions experiencing a decline in productivity (*medium confidence*). This is evident in the case of rice production, with lower yields as a result of shorter growing periods and heat-induced sterility. There are a number of regions that are already near the critical temperature threshold. In parts of Asia, increases in flood and drought will exacerbate rural poverty due to negative impacts on rice crops and increases in food prices and the cost of living (*high confidence*).			There are many potential adaptation strategies such as crop breeding, but research on their effectiveness is limited.	24.4.4, 24.4.6

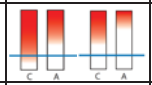
	More frequent and intense heat-waves will increase mortality and morbidity in vulnerable groups. Increases in heavy rain and temperature will increase the risk of diarrheal diseases and malaria (*high confidence*).				24.4.6
Australasia	Increasing morbidity, mortality, and infrastructure damages during heat waves in Australia, resulting from increased frequency and magnitude of extreme temperatures (*high confidence*). Vulnerable populations include the elderly, children, and those with existing chronic diseases.			Aging trends and prevailing social dynamics constrain effectiveness of adaptation responses.	25.8.1
	Significant reduction in food production in the Murray-Darling Basin, far south-eastern Australia, and some eastern and northern areas of New Zealand if scenarios of severe drying are realized (*high confidence*).			More efficient water use, allocation, and trading would increase the resilience of systems in the near term but cannot prevent significant reductions in agricultural production and severe consequences for ecosystems and some rural communities at the dry end of the projected range.	25.2, 25.5.1, 25.7.2, Box 25-5
North America	Without adaptation, projected changes in temperature, precipitation, and extreme events would result in notable productivity declines in major crops by the end of the 21st century (*very high confidence*). Given that North America is a significant source of global food supplies, there will *likely* be a negative effect on global food security if projected productivity declines are not addressed with substantial investments in adaptation (*medium confidence*).			Adaptation may ameliorate many climate impacts to agriculture, but the institutional support mechanisms currently in place are insufficient to ensure effective, equitable, and sustainable adaptation strategies.	26.5
	Given current levels of adaptation, there are *likely* to be increased health impacts from heat extremes among vulnerable communities, populations, and individuals.			Health impacts from increasing heat extremes will depend on the pace of adaptation (*high confidence*).	26.6
Central and South America	Climate-change-related changes in agricultural productivity are expected to vary greatly spatially. In Southeastern South America, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (SRES: A2, B2) (*medium confidence*). In Central America, northeast Brazil, and parts of the Andean region, increases in temperature and decreases in rainfall could decrease productivity in the short-term (before 2025), threatening food security of the poorest populations.				27.3.4
	It is *very likely* that climate variability and change may exacerbate current and future risks to health, given the region's vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, and pollution.				27.3.7
Polar Regions	Spatial convergence of impacts in different sectors creates impact "hotspots" involving new interactions, for example in the Arctic where sea ice loss and thawing disrupts transportation, buildings, other infrastructure, and potentially disrupts Inuit culture (*high confidence*).				19.3.2
	Significant impacts on the availability of key subsistence marine and terrestrial species are projected as climate continues to change with the ability to maintain economic livelihoods being affected (*high confidence*). Changing sea-ice conditions will result in more difficult access for hunting marine mammals.				28.2.6
	Increased economic opportunities and challenges for culture, security, and environment are expected with the increased navigability of Arctic marine waters and the expansion of land- and fresh water-based transportation networks (*high confidence*).				28.2.6, 28.4.2
Small Islands	Spatial convergence of impacts in different sectors creates impact "hotspots" involving new interactions, for example in the environs of Micronesia, Mariana Island, and Papua New Guinea where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification (*high confidence*).				19.3.2

Table TS.6: Assessment of climate change impacts by European sub-region and sector (by 2050, medium emissions) With economic development, with land use change. No further planned adaptation. [Table 23-4]

	Alpine	Southern	Northern	Continental	Atlantic	
Infrastructure						
Wind energy production		[1]				23.3.4
Hydropower generation	[2]					23.3.4
Thermal power production						23.3.4, 8.2.3.2
Energy consumption (net annual change)						23.3.4, 23.8.1
Road accidents [3]						23.3.3
Rail delays (weather-related)	?	?		?	[4]	23.3.3, 8.3.3.6
Load factor of inland ships	?	?	?			23.3.3
River flood damages	?	?	?			23.3.1
Transport time and cost in ocean routes	?	?			?	23.3.3, 18.3.3.3.5
Length of ski season		?			?	23.3.6, 3.5.7
Food and Fibre production						
Wine production	?		?			23.3.5, 18.3.3.1, 23.4.1
Arable Production						23.4.1
Livestock production						23.4.2
Water availability for agriculture						23.4.3
Forest productivity	?			?		23.4.4
Pest and plant diseases						23.4.1, 23.4.4
Bioenergy production	?			?	?	23.4.5
Health and Social Impacts						
Heat wave mortality						23.5.1
Damage on cultural buildings						23.5.4
Loss of cultural landscapes		?				23.5.4
Enviromental quality						

Air quality (ozone background levels)	?	?	?	?	?	23.6.1
Water quality	→	↘	→	→	↘	23.6.3
Local loss of native species and extinction of species	↗	↗	↗	↗→	↗	23.6.4

Code. Green means a "beneficial change" and Red means a "harmful", ? No relevant literature found

↗ Increasing

→ No change in

↘ Decreasing

↗→ A range from no change to increasing

→↘ A range from no change to decreasing

↗↘ A range from increasing to decreasing

FOOTNOTES

[1] Simulations have been performed, but mostly for the period after 2070.

[2] The increasing trend is for Norway.

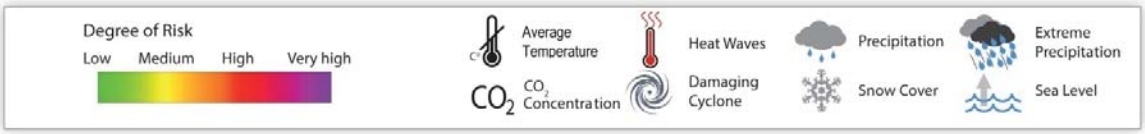
[3] The decreasing trend refers mainly to the number of severe accidents.

[4] Impacts have been studied and quantified for UK only. The increasing trend stands for summer delays and the decreasing trend for winter delays.

[5] In both seasons, no significant impacts are expected by 2020, while more substantial changes are expected by 2080. For 2050 impacts are assumed to vary linearly (although this may not be the case).

[6] The constant trend stands for the Mediterranean, where some studies estimate no changes due to climate change at least until 2030 or even 2060.

Table TS.7: Key regional risks during the 21st century from climate change for Australia and New Zealand. Color bars indicate risk as a function of global mean temperature relative to pre-industrial, based on the studies assessed and expert judgement, for the current (top bar) and a hypothetical fully adapted state (bottom bar). For each risk, relevant climate variables and trends are indicated by symbols, in approximate order of priority. Where relevant climate projections span a particularly wide range even for a given amount of global mean temperature change, risks are shown in two pairs for high and low end projections, each without and with effective adaptation*. [Table 25-8]



Arrows show projected future changes in key drivers under a range of climate and mitigation scenarios. Arrows pointing in both directions indicate that the direction of change (indicated by red and blue colours) is uncertain. Narrow horizontal bars indicate the range of potential changes, with more bars indicating greater uncertainty. Thick bars are used where the direction of change is highly certain and some amount of further change over the 21st century is virtually unavoidable even under mitigation scenarios.

Key Regional Risk		Risk for current and hypothetical fully adapted state	Key Climate Drivers and Trends	Key adaptation issues / prospects
Impacts that can be delayed but now appear very difficult to avoid entirely, even with globally effective mitigation and proactive adaptation	Significant change in community structure of coral reef systems in Australia [25.6.2, 30.5, Box CC-CR]	current / adapted; 0 °C 2 °C 4 °C 6 °C	CO_2	Limited evidence for autonomous genetic adaptation of corals; other adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing
	Loss of montane ecosystems and some endemic species in Australia [25.6.1]	current / adapted; 0 °C 2 °C 4 °C 6 °C		Direct adaptation options are limited, but reducing other stresses such as pests, diseases and predator control and enhancing connectivity of habitats provides immediate co-benefits; need to consider translocation and migration
Impacts that have the potential to be severe but can be moderated or delayed significantly by globally effective mitigation and a portfolio of available adaptation measures	Wild fire damages to ecosystems and settlements and risks to human life in southern Australia and many parts of New Zealand [Table 25-1, Box 25-6]	current / adapted; 0 °C 2 °C 4 °C 6 °C		Part of integrated landscape management; trade-offs exist between different management objectives and settlement patterns and goals
	Systematic constraints on water resource use in southern Australia [25.5.1, Box 25-2, 25-9]	current / adapted; 0 °C 2 °C 4 °C 6 °C		Water resources already struggling to meet unlimited demand in many locations and exacerbated by projected population growth; effective adaptation relies on combination of demand and supply mechanisms
	Increase in morbidity and mortality and infrastructure failure during heat waves in Australia [25.7.4, 25.8.1]	current / adapted; 0 °C 2 °C 4 °C 6 °C		Linked to social dynamics and ageing population in cities; transport and power infrastructure already at coping limit in many regions, with significant financial costs from future upgrades
	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand [25.2, Table 25-1, Box 25-8, 25-9]	current / adapted; 0 °C 2 °C 4 °C 6 °C		Significant adaptation deficit in some regions to current flood risk; effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility
Impacts that have a low or currently unknown probability but cannot be ruled out even with globally effective mitigation, and would present major challenges if realized	Significant reduction in food production in the Murray-Darling Basin, far south-east Australia and eastern and northern parts of New Zealand [25.2, Table 25-1, 25.6.1, 25.7.2, Box 25-2, 25-5]	current / adapted Wet; current / adapted Dry; 0 °C 2 °C 4 °C 6 °C		Immediate co-benefits from improved management of over-allocated water resources and balancing competing demands, but the extreme dry end would threaten agricultural production as well as ecosystems and some rural communities
	Widespread damages to coastal infrastructure and low-lying ecosystems in Australia and New Zealand [Table 25-1, 25.6.1, 25.6.2, Box 25-2, 25-9]	current / adapted Low; current / adapted High; 0 °C 2 °C 4 °C 6 °C		Adaptation deficit in some locations to current coastal erosion and flood risk; successive building and protection cycles constrain flexible responses; effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation

* For rainfall and its impact on food production, wet and dry scenarios represent approximately the 10 and 90 percentile range of current model projections and RCP emissions scenarios. For sea level, the low scenario is a 0.39 m rise by 2100 (mid-range model projections, RCP 2.6); the high scenario is a 1.5 m rise by 2100 (semi-empirical models, RCP 8.5). See AR5 WGI Chap 13 for more details. Under either scenario, sea level would continue to rise beyond 2100, but the focus of the risk assessment here is for risks that could be realised during the 21st century.

Table TS.8: A selection of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in the report. The examples underscore the complexity of risks determined by various climatic hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, demographic changes, or tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climate-change-related harm and loss can occur. The examples illustrate that current global megatrends (e.g., climate change, urbanization, demographic changes), in combination and in specific development contexts (e.g., in low-lying coastal zones), can generate new systemic risks that go far beyond existing adaptation and risk management capacities, particularly in highly vulnerable regions. [Table 19-3]

Hazard/Stressor	Key vulnerabilities	Key risks	Emergent risks
Examples from terrestrial and inland water systems			
Rising air, soil, and water temperature.	Exceedence of eco-physiological climate tolerance limits of species, increased viability of alien organisms.	Loss of native biodiversity, increase in alien organism dominance.	Cascades of native species loss due to interdependencies.
	Epidemiological response to spread of temperature-sensitive vectors (insects).	Novel or much more severe pest and pathogen outbreaks.	Interactions between pest, drought, and fire interactions can lead to new risks and large negative impacts on ecosystems.
Examples from ocean systems			
Rising water temperature, increase of (thermal and haline) stratification, and marine acidification. [6.1.1] *(also Chapter 24)*	Tolerance limits of endemic species surpassed, increased abundance of invasive organisms, high vulnerability of warm water coral reefs and respective ecosystem services for coastal communities. [6.2.2, 6.2.5]	Loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms, loss of coral cover and associated ecosystems with reduction of biodiversity. [6.3.2]	Enhancement of risk due to interactions, e.g., acidification and warming for calcareous organisms. [6.3.5]
Examples from urban areas			
Inland flooding.	Urban areas with large numbers of poor, uninsured people exposed to flood events including low-income informal settlements. Environmental health consequences from overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure combined with widespread impermeable surfaces. Inadequate local governance. Increased mosquito and water borne diseases.	Increasing urban flooding with increasing volume and velocity of flood waters on the one hand and increasing vulnerability on the other leads to key risks particularly in urban areas with large numbers of people who are poor and/or exposed to flooding.	Larger and more frequent flooding impacting a much larger population. Impacts reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight; abandonment of urban districts and the creation of high risk/high poverty spatial traps.
Changing hazard profile including novel hazards and new multi-hazard complexes.	Newly exposed populations and infrastructure, especially for those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks.	Risks from failures within coupled systems, e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications, psychological shock from unanticipated risks.	Loss of faith in risk management institutions. Potential for large events that are magnified by a lack of preparation and capacity to respond.
Examples from human health			
Increasing frequency and intensity of extreme heat. *(also chapter 19)*	Older people living in cities are most vulnerable to heat waves, and their population is projected to triple from 2010-2050.	Increased mortality and morbidity during heat waves, particularly in people with pre-existing conditions.	Overloading of health and emergency services. Mortality, morbidity, and productivity loss, particularly for manual workers in hot climates.
Increasing temperatures, increased variability in precipitation.	Food insecurity translates into malnutrition, which is among the largest disease burdens in poorer populations.	Progress in reducing mortality and morbidity from malnutrition may slow or reverse and constitutes a new key risk.	Combined impacts of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequity, and on-going food insecurity for the poor.
Examples from livelihoods and poverty			
Soaring demand (and prices) of biofuels due to climate change policies.	Unclear and/or insecure land tenure arrangements.	Risk of dispossession of land due to "land grabbing" in developing countries.	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production.
Increasing frequency of extreme events (droughts, floods). For example if 1:20 year drought/flood becomes 1:5 year flood/drought.	Livelihoods subject to damage to their productive assets (e.g. in case of droughts – herds of livestock; if floods – dikes, fences, terraces).	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years.	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.

Hazard/Stressor	Key vulnerabilities	Key risks	Emergent risks
Examples from Chapter 19			
Warming and drying (degree of precipitation changes uncertain). [WGI AR5 SPM, TS.5.3, 11.3, 12.4]	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; socio-cultural constraints on some adaptation options. [19.2.2, 19.3.2, 19.6.1, 19.7.5]	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition, limited coping and adaptation options increase the risk of harm and loss. [19.3.2]	Negative outcomes to sending and/or receiving regions from migration of populations due to limits on agricultural productivity and livelihoods. [19.3.2, 19.4.2]
Examples from Africa			
Increasing temperature.	Health of exposed and vulnerable groups (increased exposure to heat, change in the transmission dynamics of vector-borne diseases).	Increase in disease burden – changes in the patterns of infection. Decrease in outdoor worker productivity due to high temperature, increase in heat related morbidity and mortality.	Emerging and re-emerging disease epidemics.
	Vulnerability of aquatic systems and vulnerability of aquatic ecosystem services due to increased water temperatures.	Loss of aquatic ecosystems and risks for people who might depend on these resources.	
Examples from Europe			
Extreme weather events. *(also Chapter 19)*	Limited coping and adaptive capacity as well as high sensitivity of different sectors, e.g., transport, energy, and health.	Stress on multiple sectors can cause systemic risks due to interdependencies among sectors.	Disproportionate intensification of risk due to increasing interdependencies.
Examples from Asia			
Thawing of permafrost due to rising temperature in northern Asia.	Existence of structures and infrastructure on permafrost and high dependence of civil life on them.	Instability of or damage to structures and infrastructures.	Projected exacerbation of instability of residential buildings, pavements, pipelines used to transport petroleum and gas, pump stations, and extraction facilities.
Projected increase in frequency of various extreme events (heat waves, floods, and droughts) and sea level rise. *(also Chapter 19)*	Convergence of livelihoods and properties into coastal megacities, especially into areas not sufficiently protected against natural hazards.	Loss of human life and assets due to coastal floods accompanied by increasing vulnerabilities caused by occurrence of other extreme events like heat waves and droughts.	Projected increase in disruption of basic services such as water supply, sanitation, energy provision, and transportation systems, which themselves could increase vulnerabilities.
Examples from Australasia			
Warming and increased temperature high extremes in Australia. [25.2, Table 25-1, Figure 25-5]	Urbanization, aging of population and vital infrastructure. [25.3, Box 25-9, 25.10.2]	Increase in morbidity, mortality, and infrastructure failure during heat waves. [25.8.1, 25.10.2]	Increasing risk from compound extreme events across time, space and governance scales, and cumulative adaptation needs. [25.10.2, 25.10.3, Box 25-9]
Potential for sea level rise beyond 2100 exceeding 1m [25.2, WGI AR5 Chapter 13]	Long lifetime of coastal infrastructure, concentration and further expansion of coastal population and assets; conflicting priorities and time preferences constraining adaptation options; limited scope for managed retreat in highly developed areas.	Widespread damages to coastal infrastructure and low-lying ecosystems. [Box 25-1, 25.10.2]	
Examples from North America			
Increases in frequency and/or intensity of extreme events, such as hurricanes, river and coastal floods, heat waves, and droughts. [26.2] *(also Chapter 19)*	Declining state of physical infrastructure in urban areas as well as increases in income disparities. [26.7]	Risk of serious harm and losses in urban areas, particularly in coastal environments due to enhanced vulnerabilities of social groups and physical systems combined with increases of extreme weather events. [26.8]	Inability to reduce vulnerability in many areas results in increase in risk greater than change in physical hazard. [26.8]
Higher temperatures, decreases in runoff, and lower soil moisture. [26.2, 26.3]	Increasing vulnerability of small landholders in agriculture. [26.5]	Increased losses and decreases in agricultural production increase food and job insecurity for small landholders and social groups in that region. [26.5]	Increasing risks of social instability and local economic disruption due to internal migration. [26.2, 26.8]

Table TS.9: Examples of potential trade-offs among adaptation objectives. [Table 16-2]

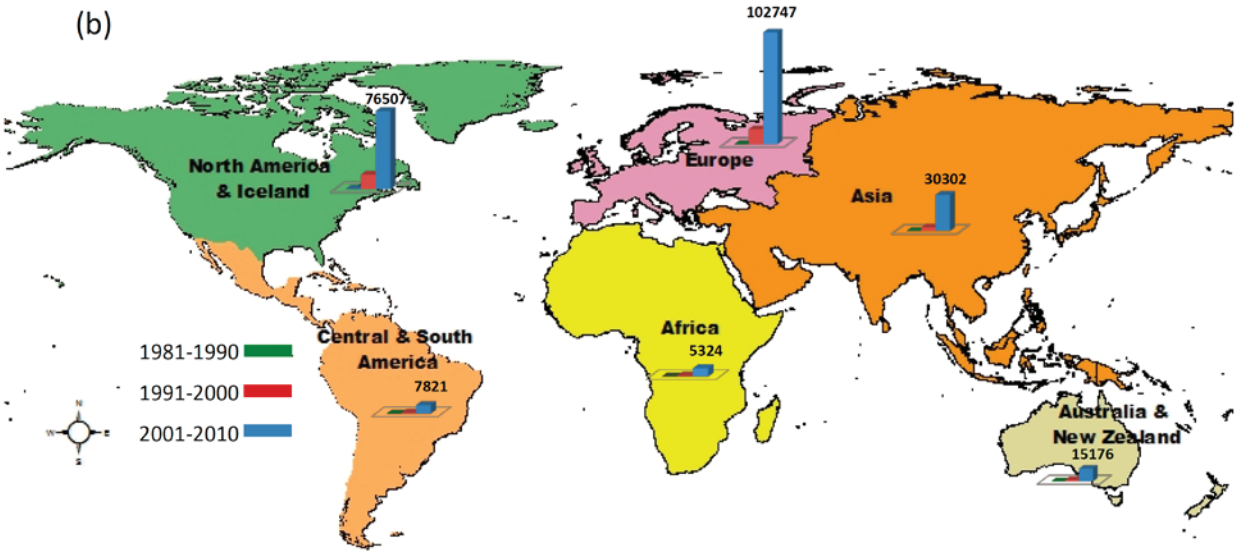
Sector	Strategy	Adaptation Objective	Real or Perceived Externality
Agriculture	Biotechnology and genetically modified crops	Enhance drought and pest resistance; enhance yields	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments
	Subsidized drought assistance; crop insurance	Provide financial safety net for farmers to ensure continuation of farming enterprises	Creates moral hazard and inequality if not appropriately administered
	Increased use of chemical fertilizer and pesticides	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased discharge of nutrients and chemical pollution to the environment; increased emissions of greenhouse gases; increased human exposure to pollutants
Biodiversity	Migration corridors; expansion of conservation areas	Enable natural adaptation and migration to changing climatic conditions	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges
	Anticipatory endangerment listings	Enhance regulatory protections for species potentially at-risk due to climate change	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to economic development
	Assisted migration	Facilitate conservation of valued species	Potential for externalities for ecological and human systems due to species relocation
Coasts	Sea walls	Protect assets from inundation and/or erosion	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands
	Managed retreat	Allow natural coastal and ecological processes; reduce long-term risk to property and assets	Undermines private property rights; significant governance challenges associated with implementation
	Migration out of low-lying areas	Preserve public health and safety; minimize property damage and risk of stranded assets	Loss of sense of place and cultural identify; erosion of kinship and familial ties; impacts to receiving communities
Water resources management	Desalination	Increase water resource reliability and drought resilience	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation
	Water trading	Maximize efficiency of water management and use; increases flexibility	Undermines public good/social aspects of water
	Water recycling/reuse	Enhance efficiency of available water resources	Perceived risk to public health and safety

Table TS.10: Illustrative examples of intra-regional interactions among adaptation, mitigation, and sustainable development.

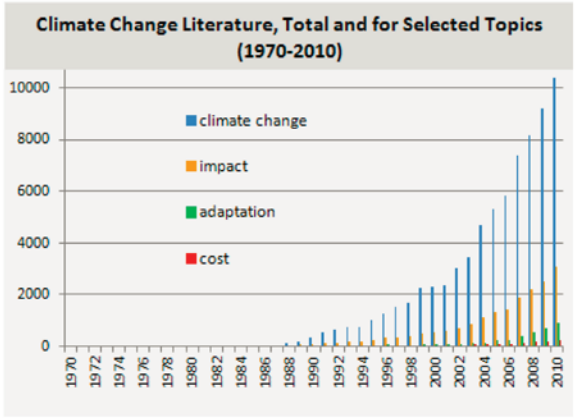
Green infrastructure and green roofs	
Objectives: *Storm water management, adaptation to increasing temperatures, reduced energy use, urban regeneration*	
Relevant Sectors: *Infrastructure, energy use, water management*	
Overview: Benefits of green infrastructure and roofs can include reduction of storm water runoff and the urban heat island effect, improved energy performance of buildings, reduced noise and air pollution, health improvements, better amenity value, increased property values, improved biodiversity or species migration, and inward investment. Trade-offs can result between higher urban density to improve energy efficiency and open space for green infrastructure. [8.3.3.7, 14.2.2.1, 17.4.1, 23.7.4, table 25-6]	
Location	**Example, with interactions**
London	The Green Grid for East London seeks to create interlinked and multi-purpose open spaces to support regeneration of the area. It aims to connect people and places, to absorb and store water, to cool the vicinity, and to provide a diverse mosaic of habitats for wildlife. [8.3.3]
New York	In preparation for more intense storms, New York is using green infrastructure to capture rainwater before it can flood the combined sewer system; implementing green roofs, blue roofs, and porous pavements for streets; and elevating boilers and other equipment above ground. [26.4.3]
Singapore	Singapore has used several anticipatory plans and projects to enhance green infrastructure including its Streetscape Greenery Master Plan, constructed wetlands or drains, and community gardens. Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives. [8.3.3]
Durban	In Durban, ecosystem-based adaptation is part of its climate change adaptation strategy, seeking a more detailed understanding of the ecology of indigenous ecosystems and ways in which biodiversity and ecosystem services can reduce vulnerability of ecosystems and people. Examples include a pilot green roof project and its Community Reforestation Programme in which communities produce indigenous seedlings used in the planting and managing of restored forest areas. Needs for knowledge, new data collection, expertise, and resources, along with direct and immediate developmental co-benefits, have been identified in developing a network of bio-infrastructure. [8.3.3]

Water management	
Primary Objective: *Water resource management given multiple stressors in a changing climate*	
Relevant Sectors: *Water use, energy use, biodiversity*	
Location	**Example, with interactions**
New York	New York has a well-established program to protect and enhance its water supply through watershed protection. The Watershed Protection Program includes city ownership of land that remains undeveloped and coordination with landowners and communities to balance water-quality protection, local economic development, and improved wastewater treatment. The city government indicates it is the most cost-effective choice for New York given the costs and environmental impacts of a filtration plant. [8.3.3]
Africa	Water stress has encouraged dam construction to ensure water resource resiliency, but in some parts of Africa this has resulted in deleterious health impacts. Dam building can stimulate the reproduction of parasites in lakes nearby human settlements, amplifying the risk of schistosomiasis and leishmaniasis. [22.3.5]
Capital cities in Australia	Many Australian capital cities are reducing reliance on catchment runoff and groundwater—water resources most sensitive to climate change and drought—and are diversifying supplies through desalination plants, water reuse including sewage and storm water recycling, and integrated water cycle management that considers climate change impacts. Demand is being reduced through water conservation and water sensitive urban design and, during severe shortfalls, through implementation of restrictions. The water augmentation program in Melbourne includes a desalinization plant. Trade-offs beyond energy intensiveness have been noted, such as damage to sites significant to aboriginal communities and higher water costs that will disproportionately affect poorer households. [Box 25-2, 14.7.2]

Payment for environmental services and green fiscal policies	
Primary Objective: *Management incorporating the costs of environmental externalities and the benefits of ecosystem services*	
Relevant Sectors: *Biodiversity, ecosystem services*	
Location	**Example, with interactions**
Central and South America	A variety of payment for environmental services (PES) schemes have been implemented in Latin America. For example, national-level programs have operated in Costa Rica and Guatemala since 1997 and in Ecuador since 2008. Examples to date have shown that PES can finance conservation, ecosystem restoration and reforestation, and better land-use practices. Uniform payments for beneficiaries can be inefficient if, for example, recipients that promote greater environmental gains receive only the prevailing payment. [27.3.2, 27.6.2, table 27-8, 17.5.2, 17.5.4]
Brazil	Municipal funding in Brazil tied to ecosystem-management quality is a form of revenue transfer important to funding local adaptation actions. State governments collect a value-added tax redistributed among municipalities, and some states allocate revenues in part based on municipality area set aside for protection. This mechanism has helped improve environmental management and increased creation of protected areas. It benefits relations between protected areas and surrounding inhabitants, as the areas can be perceived as opportunities for revenue generation rather than as obstacles to development. The approach builds on existing institutions and administrative procedures and thus has low transaction costs. [8.4.3, Box 8-3]
Renewable energy	
Primary Objective: *Renewable energy production and reduction of emissions*	
Relevant Sectors: *Biodiversity, agriculture, food security*	
Location	**Example, with interactions**
Central and South America	Renewable resources, especially hydroelectric power and biofuels, account for substantial fractions of energy production in countries such as Brazil. Where bioenergy crops compete for land with food crops, substantial trade-offs can exist. Land-use change to produce bioenergy can affect food crops, biodiversity, and ecosystem services. Lignocellulosic feedstocks, such as sugarcane second-generation technologies, do not compete with food. [27.3.6, Table 27-6]
Australia and New Zealand	Mandatory renewable energy targets and incentives to increase carbon storage support both increased biofuel production and increased biological carbon sequestration, with impacts on biodiversity depending on implementation. Benefits can include reduced erosion, additional habitat, and enhanced connectivity, with risks or lost opportunities associated with large-scale monocultures especially if replacing more diverse systems. Large-scale land-cover changes can affect catchment yields and regional climate in complex ways. New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services. [Box 25-10, Table 25-6]



(a)

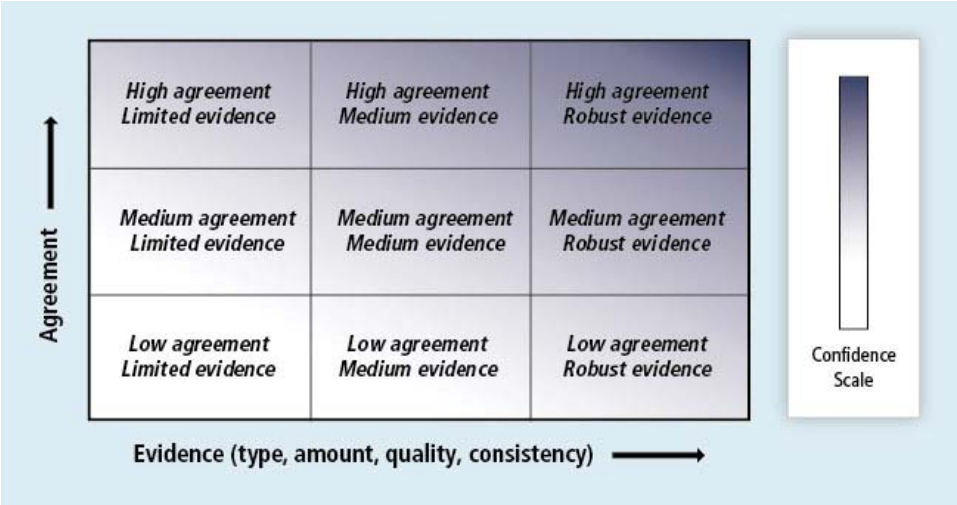


(c)

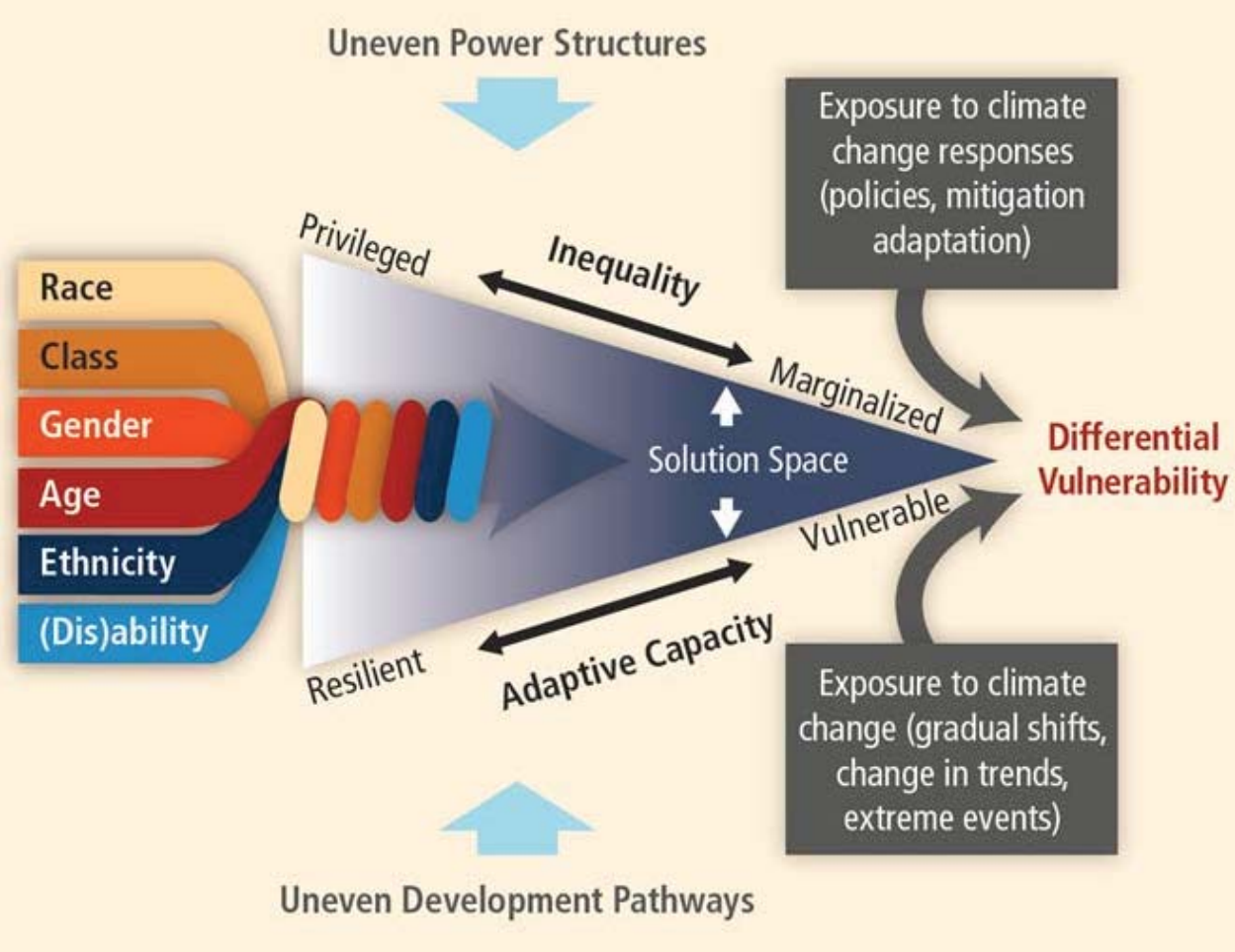
Climate Change Literature by Region (Title, Key Words, or Abstract)

	1981-1990	1991-2000	2001-2010
Africa	0	509	4815
Asia	9	2821	27472
Europe	71	12218	90458
North America	290	11926	64281
Central and South America	2	677	7142
Australia and New Zealand	7	1654	13515

Box TS.1 Figure 1: Results of English literature search using the Scopus bibliographic database from Reed Elsevier Publishers. (a) Annual global output of publications on climate change and related topics: impacts, adaptation, and costs (1970-2010). (b) Country affiliation of authors of climate change publications summed for IPCC regions for three time periods: 1981-1990, 1991-2000, and 2001-2010, with total number during the period 2001-2010. (c) Results of literature searches for climate change publications with individual countries mentioned in publication title, abstract, or key words, summed for all countries by geographic region. [Figure 1-1]



Box TS.3 Figure 1: Evidence and agreement statements and their relationship to confidence. The shading increasing towards the top right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence. [Figure 1-4]



Box TS.4 Figure 1: Intersecting yet simultaneous and dynamic axes of privilege and marginalization, shaped by people's multiple identities and embedded in uneven power relations and development pathways. Together, they result in differential vulnerability to the same exposure to climate change and climate change responses. These intersecting dimensions ("intersectionality") illustrate systemic vulnerability and multidimensional deprivation that determine inequality and adaptive capacity while being transformed as a result of negative climate change impacts and risks as well as consequences of policy responses, often to the detriment of the poor and disadvantaged. [Figure 13-4]

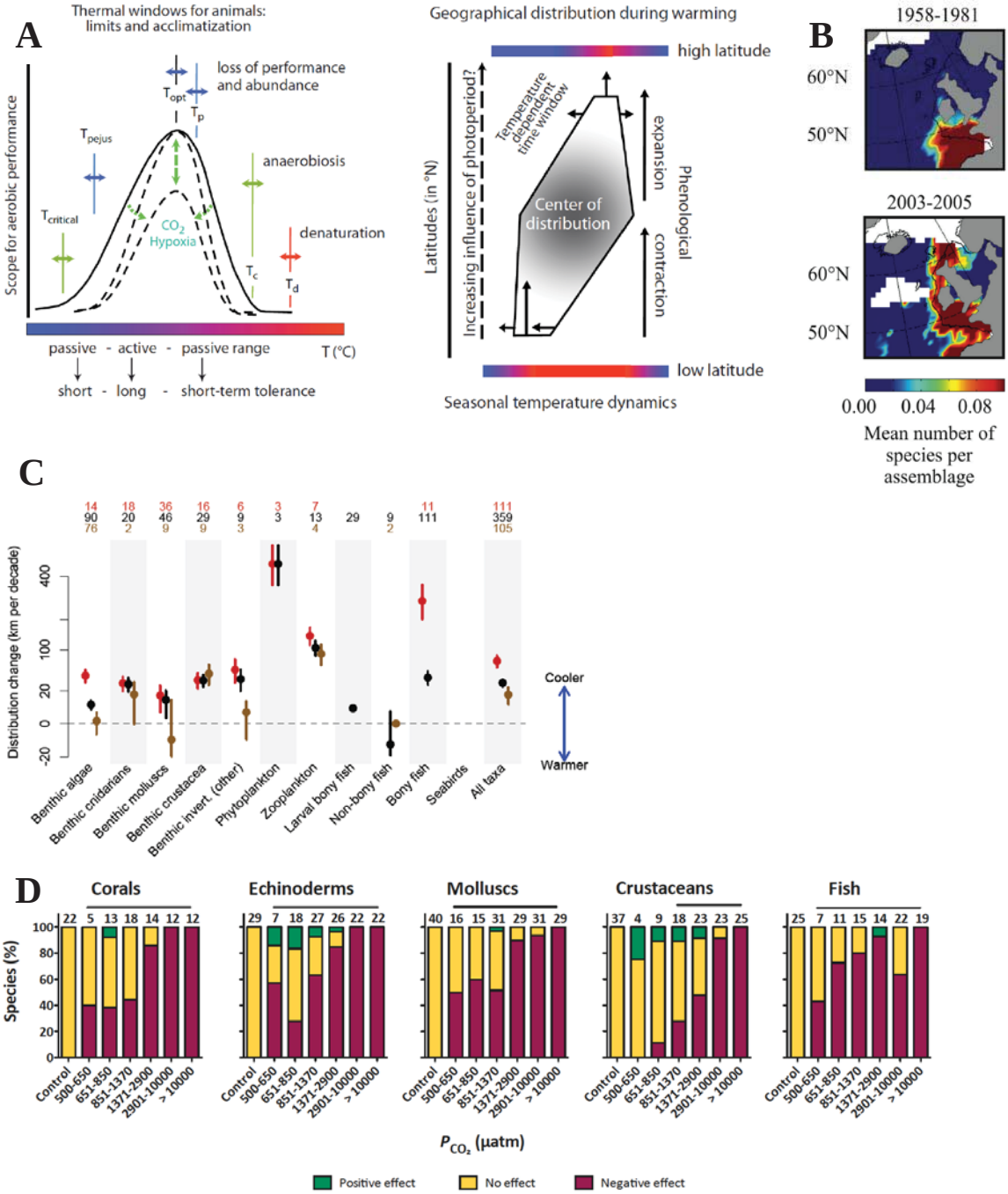


Figure TS.1: Thermal specialization of species, sensitive to ocean acidification and hypoxia (A, left) causes warming induced distribution shifts (A, right). An example (B) is the northward expansion of warm-temperate species in the Northeast Atlantic. Differential distribution change across functional groups (C) will be influenced by species-specific impacts of future ocean acidification across phyla (D). Detailed introduction of each panel follows: A) Mechanisms linking organism to ecosystem response explain the why, how, when, and where of climate sensitivity (blue to red color gradients illustrate transition from cold to warm temperatures). As all biota, animals specialize on limited temperature ranges, within which they grow, behave, reproduce, and defend themselves by immune responses (left). Optimum temperatures (T_{opt}) indicate performance maxima, pejus temperatures (T_p) the limits to long-term tolerance, critical temperatures (T_c) the transition to anaerobic metabolism, and denaturation temperatures (T_d) the onset of cell damage. These thresholds can shift by acclimatization (horizontal arrows). Under elevated CO_2 levels and in hypoxic waters

performance levels can decrease and windows of performance be narrowed (dashed green arrows pointing to dashed black curves). Shifts in biogeography result during climate warming (right). The polygon delineates the range in space and time, the level of grey denotes abundance. Species display maximum productivity in southern spring, wide seasonal coverage in the center, and a later productivity maximum in the North. The impact of photoperiod increases with latitude (dashed arrow). During warming, the southern temperature and time window contracts while the northern one dilates (directions and shifts indicated by arrows). Control by water column characteristics or photoperiod may overrule temperature control in some organisms (e.g., diatoms), causing contraction of spatial distribution in the north. B) Long-term changes in the mean number of warm-temperate pseudo-oceanic species in the Northeast Atlantic from 1958 to 2005. C) Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, with number of observations and significance (*p<0.1, **p<0.05, ***p<0.01). D) % fraction of studied scleractinian coral, echinoderm, molluscan, crustacean, and fish species affected negatively, positively, or not at all by various levels of ambient CO_2. Effects considered include those on life stages and processes reflecting physiological performance (O_2 consumption, aerobic scope, behaviors, scope for behaviors, calcification, growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, morphology). Horizontal bars above columns represent frequency distributions significantly different from controls. [Figures 6-7, 6-10, 6-11, and 30-11]

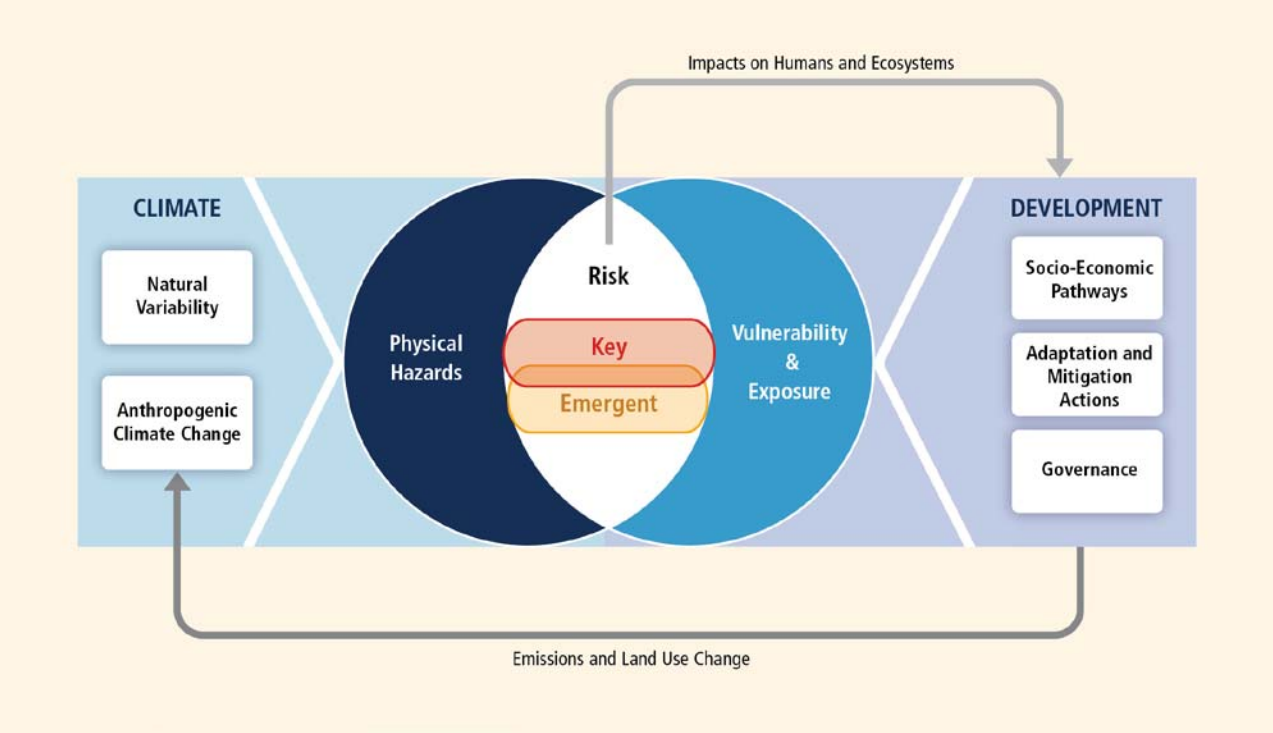


Figure TS.2: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. Risks are a product of a complex interaction between physical hazards associated with climate change and climate variability on the one hand, and the vulnerability of a society or a social-ecological system and its exposure to climate-related hazards on the other. The definition and use of “key” and “emergent” are indicated in Section C.ii. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions. Changes in both the climate system (left side) and development processes (right side) are key drivers of the different core components (vulnerability, exposure, and physical hazards) that constitute risk. [19.1, Figure 19-1]

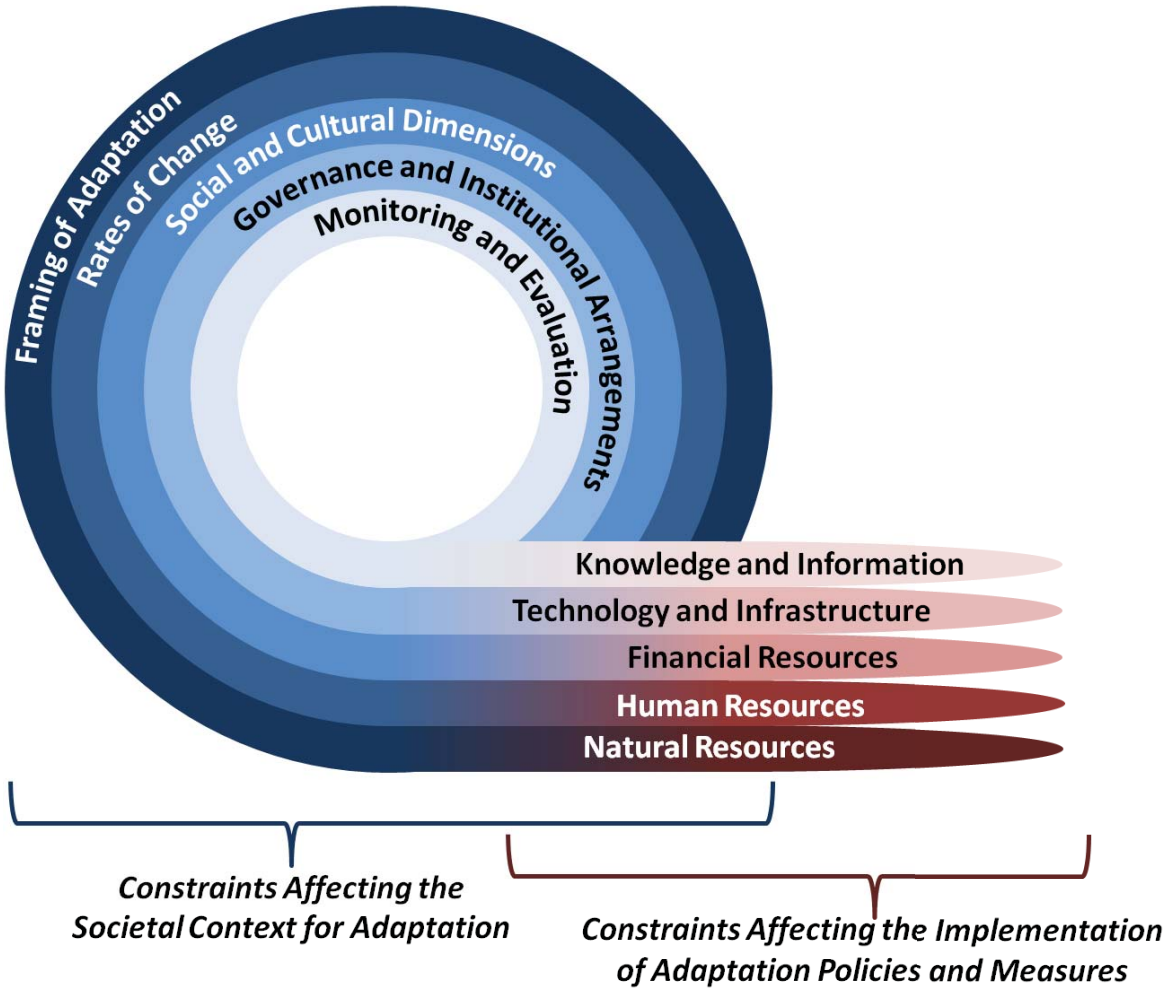


Figure TS.3: Key adaptation constraints assessed, categorized into two groups. One group reflects constantly evolving biophysical and socio-economic processes that influence the societal context for adaptation. These processes subsequently influence the second group of constraints affecting the implementation of specific adaptation policies and measures that could be deployed to achieve a particular objective. [Figure 16-2]

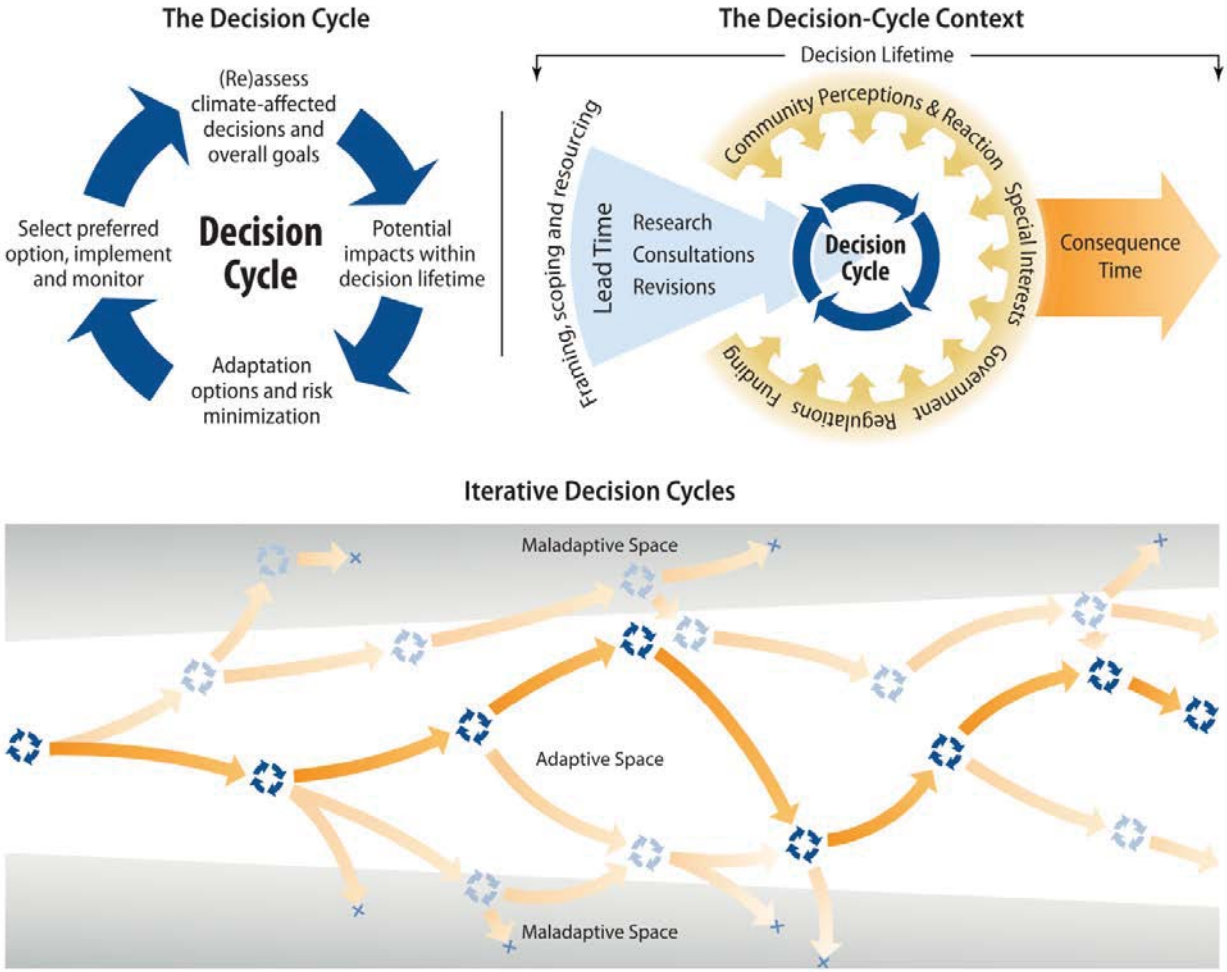


Figure TS.4: Schematic illustration of adaptation as an iterative risk management process. Each individual adaptation decision comprises well known aspects of risk assessment and management (top left panel). Each such decision occurs within and exerts its own sphere of influence, determined by the lead and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single correct adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations, and goals. [Figure 25-6]

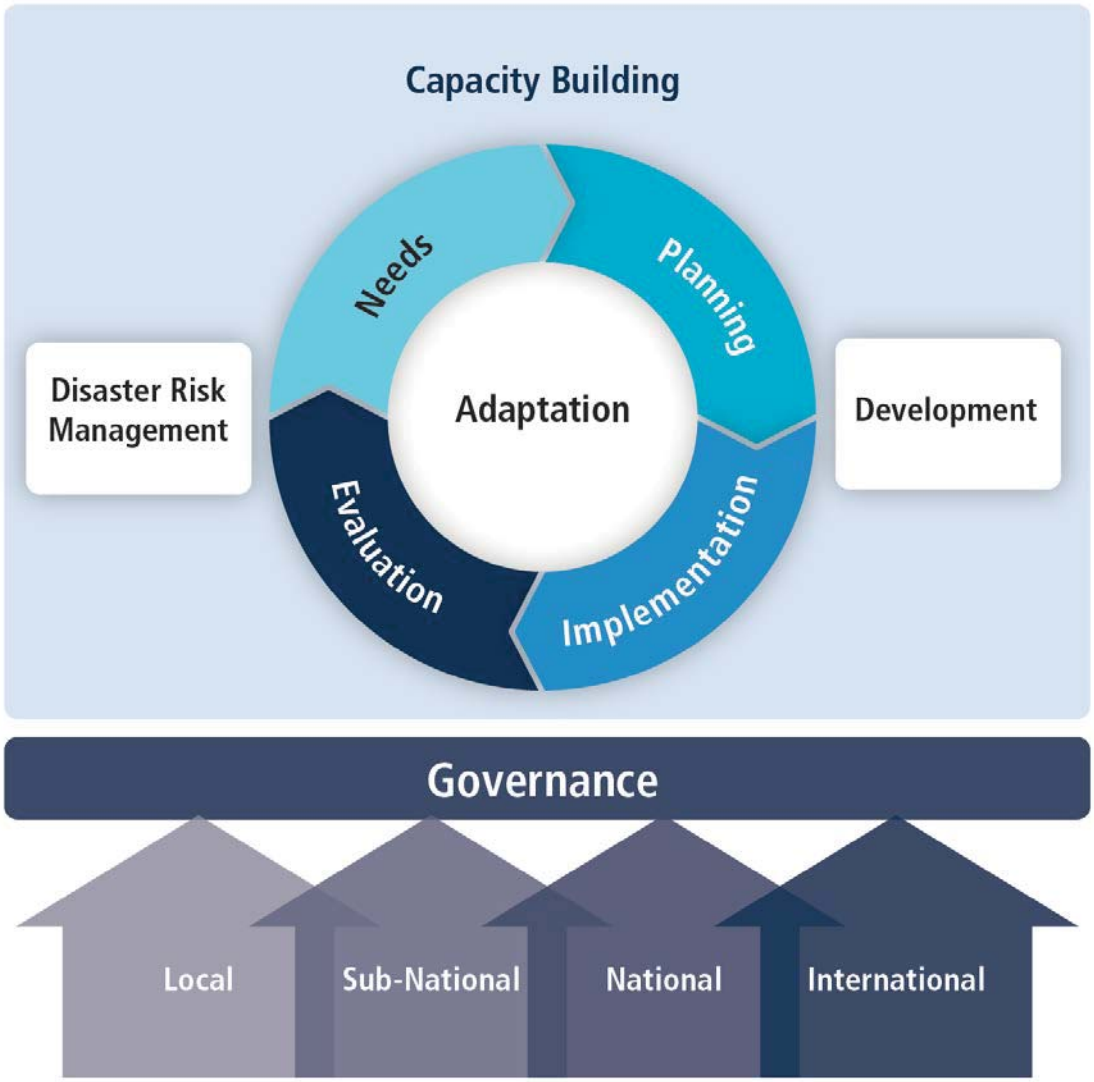


Figure TS.5: Four main phases of adaptation planning and implementation: needs, planning, implementation, and evaluation. This is a cyclic, iterative process. Building capacity to respond to change, whether expected or unexpected, creates resilience in societies to cope in the face of uncertainties in climate change projections. Efforts in adaptation can be linked with development or disaster risk management. Adaptation governance underlies capacity, and governance takes place at multiple scales: international, national, sub-national, and local. [Figure 15-1]

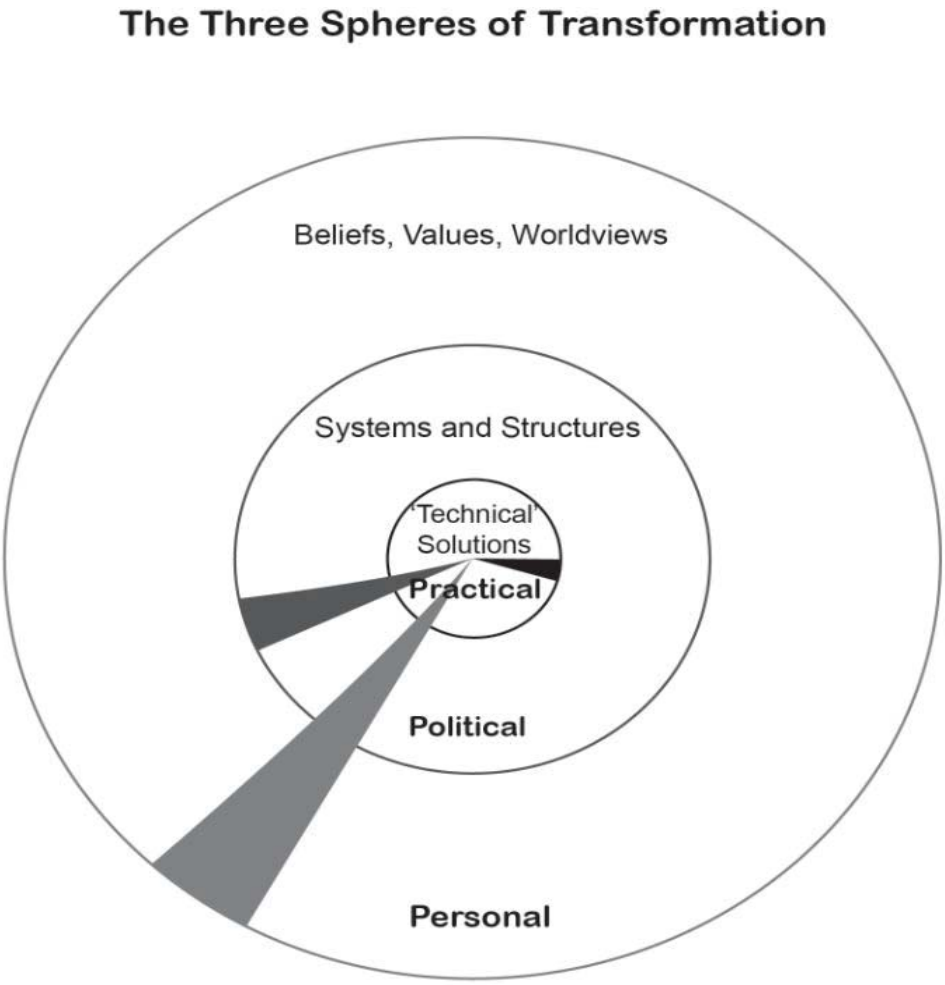
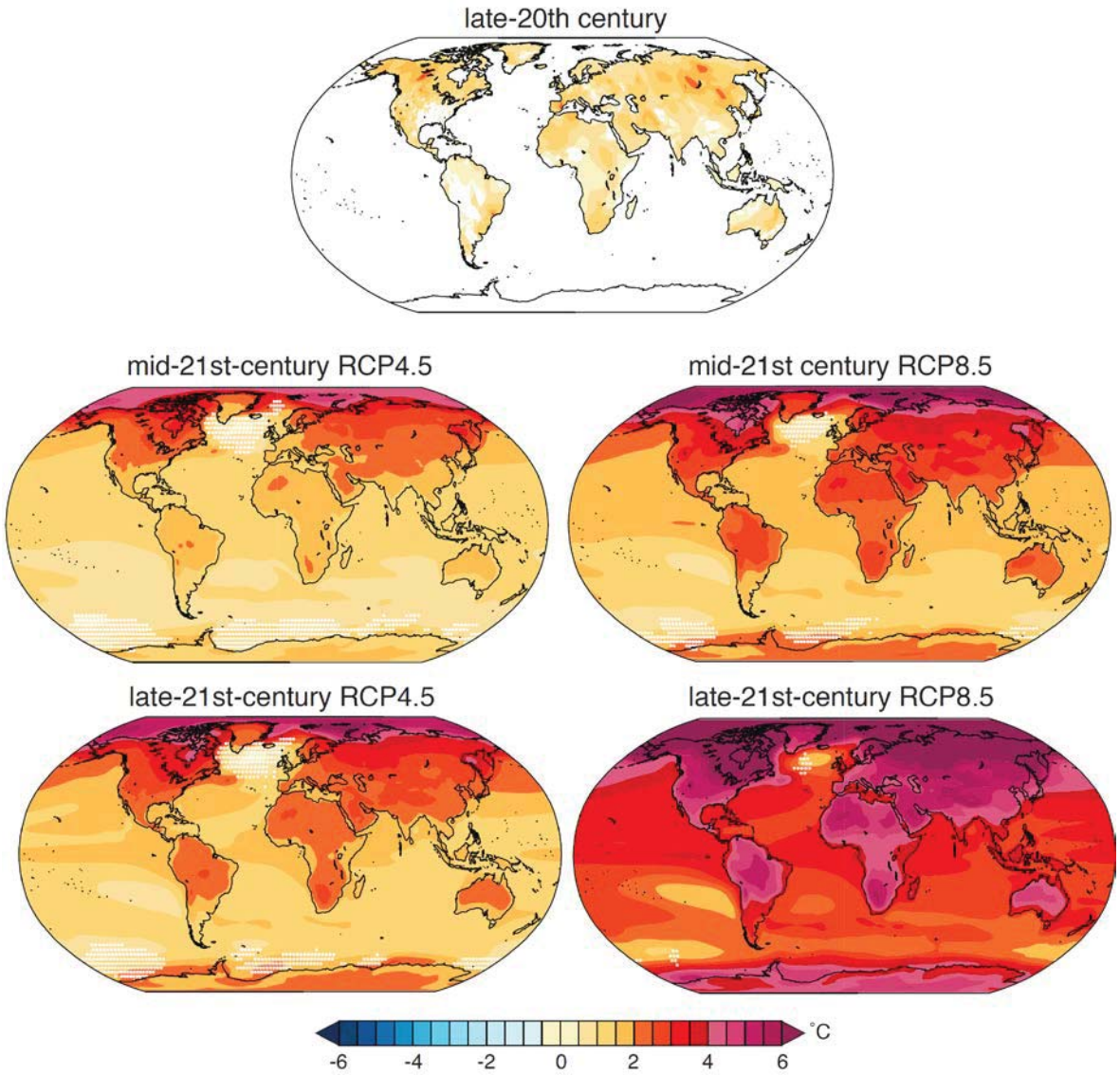
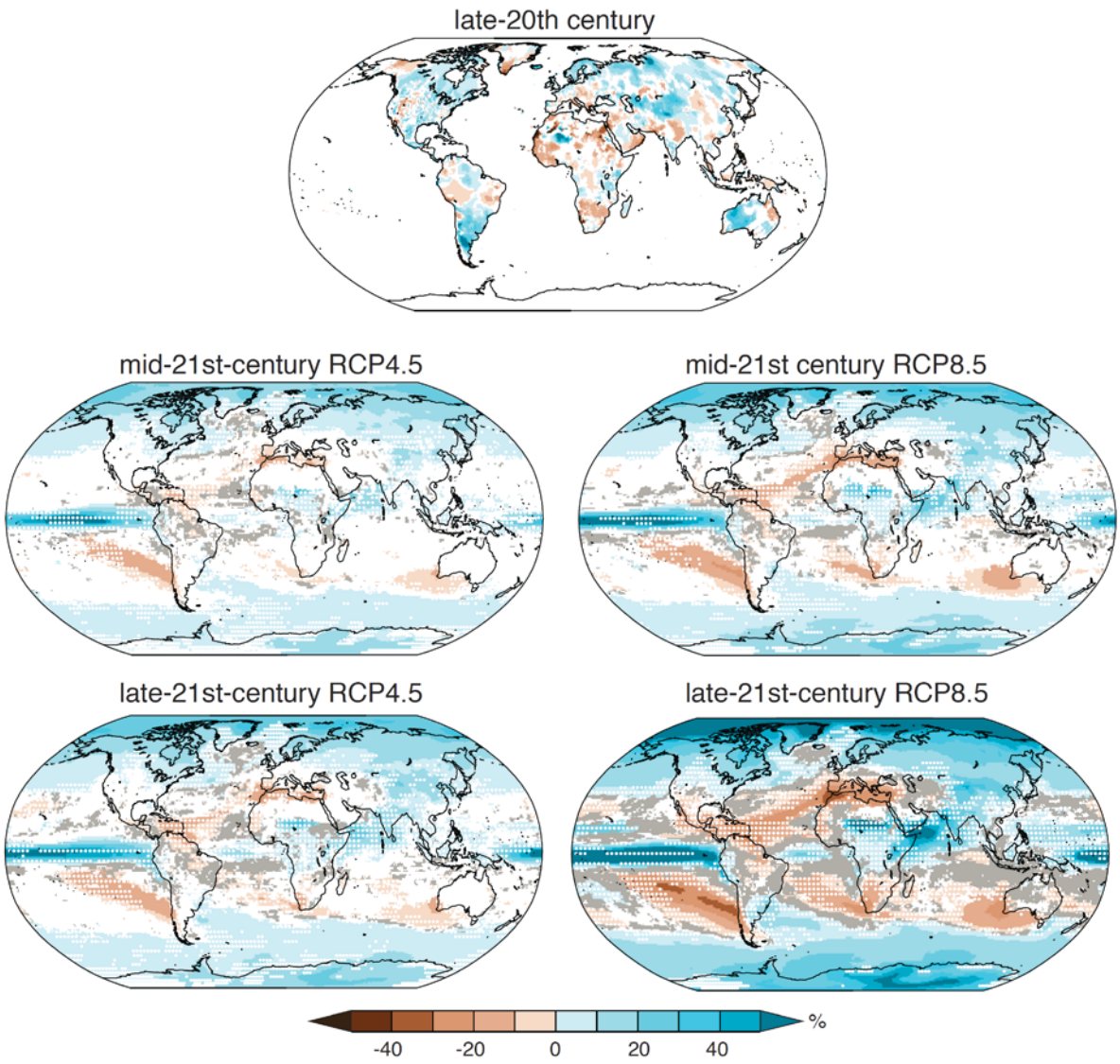


Figure TS.6: The practical, political, and personal spheres of transformation. [20.5.2, Figure 20-2]



Box TS.5 Figure 1: Change in annual average temperature (A) and precipitation (B). For observations (top map, A and B; CRU), differences are shown over land between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For projections (bottom four maps, A and B; CMIP5), four classes of results are displayed. (1) White indicates areas where for >66% of models the annual average change is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions, more than 2/3 of models show no significant change, using this measure of significance, in the annual average, although this does not imply no significant change at seasonal or shorter time-scales such as months to days. (2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions, more than 2/3 of models show a significant change in annual average, but less than 2/3 agree on whether it will increase or decrease. (3) Colors with circles indicate the change averaged over all models where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on whether the annual average will increase or decrease. In these regions, more than 2/3 of models show a significant change in annual average and more than 2/3 (but less than 90%) agree on whether it will increase or decrease. (4) Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether the annual average will increase or decrease. For models that have provided multiple realizations for the climate of the recent past and the future, results from each realization were first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios were calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065. See also Annex I of WGI AR5. [Box CC-RC]



Box TS.5 Figure 1: Change in annual average temperature (A) and precipitation (B). For observations (top map, A and B; CRU), differences are shown over land between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For projections (bottom four maps, A and B; CMIP5), four classes of results are displayed. (1) White indicates areas where for >66% of models the annual average change is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions, more than 2/3 of models show no significant change, using this measure of significance, in the annual average, although this does not imply no significant change at seasonal or shorter time-scales such as months to days. (2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions, more than 2/3 of models show a significant change in annual average, but less than 2/3 agree on whether it will increase or decrease. (3) Colors with circles indicate the change averaged over all models where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on whether the annual average will increase or decrease. In these regions, more than 2/3 of models show a significant change in annual average and more than 2/3 (but less than 90%) agree on whether it will increase or decrease. (4) Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether the annual average will increase or decrease. For models that have provided multiple realizations for the climate of the recent past and the future, results from each realization were first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios were calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065. See also Annex I of WGI AR5. [Box CC-RC]

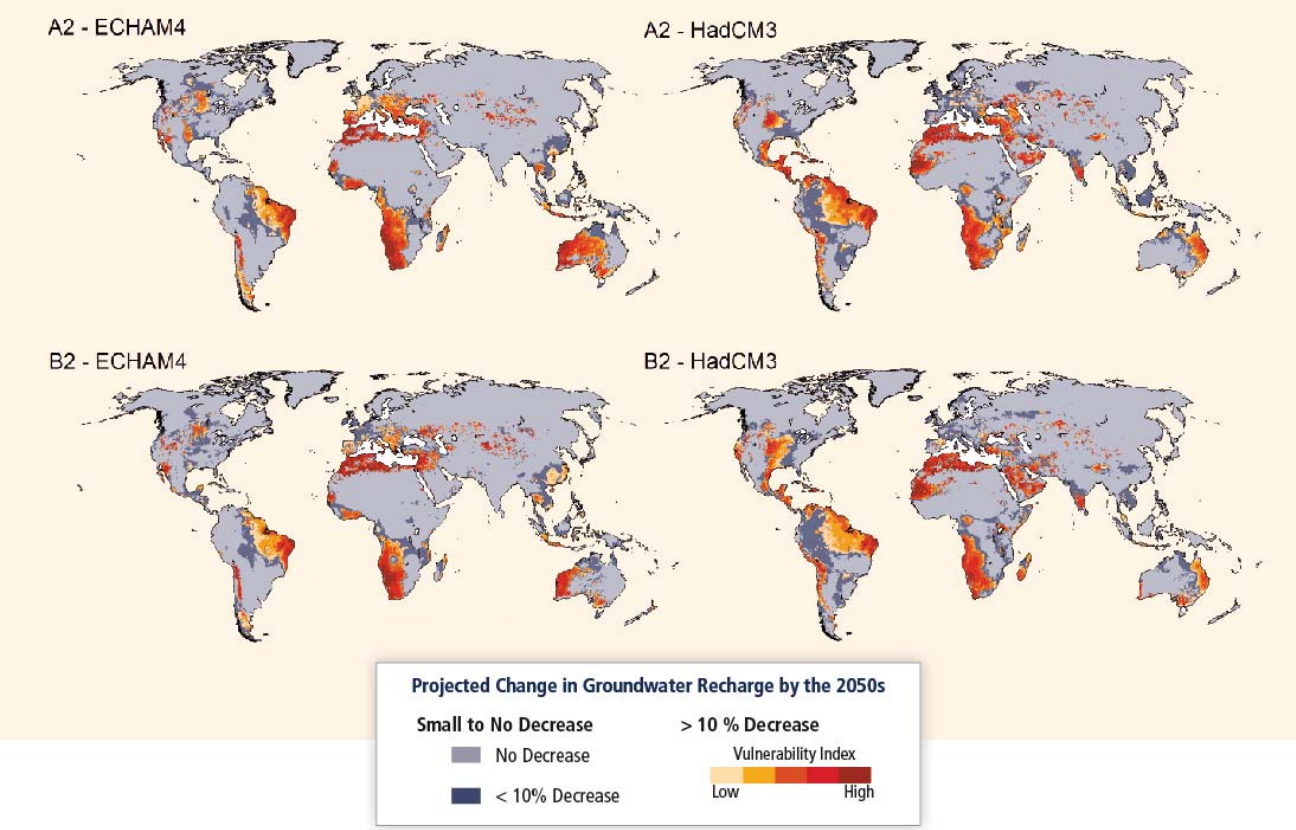


Figure TS.7: Human vulnerability to climate-change-induced decreases of renewable groundwater resources by the 2050s for lower (B2) and higher (A2) emissions pathways and two global climate models. The higher the vulnerability index (percent decrease of groundwater recharge multiplied by a sensitivity index), the higher the vulnerability. The index is computed for areas where groundwater recharge is projected to decrease by at least 10%, as compared to the reference period 1961-90. [Figure 3-9]

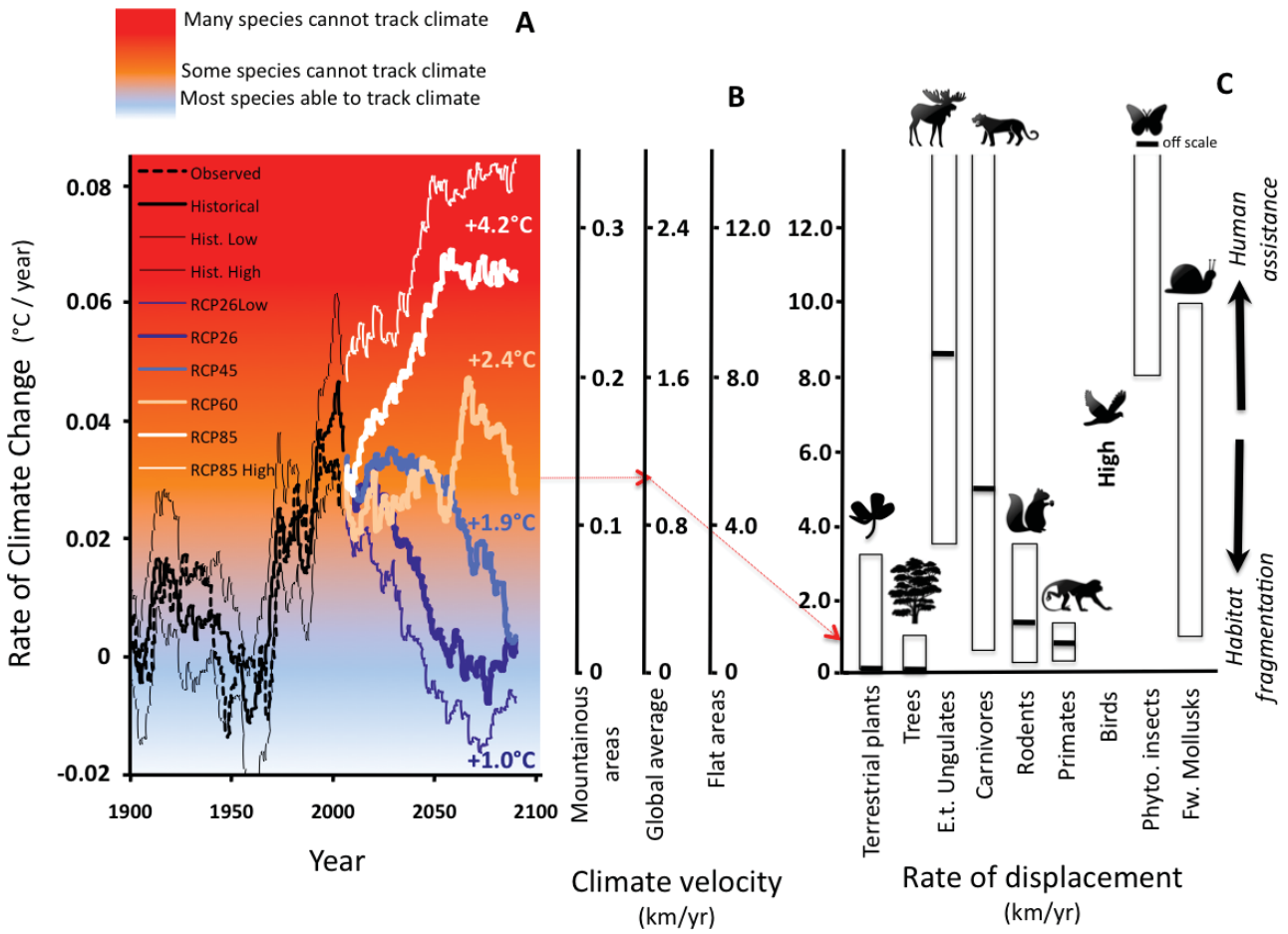


Figure TS.8: Rate of climate change (A), corresponding climate velocities (B), and rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention (C). The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.03 °C/yr correspond to ca. 1.1 km/yr global average climate velocity. When compared to rates of displacement, this would exceed rates for most plants, many primates, and some rodents. (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis; all other rates are calculated based on the average of the CMIP5 climate model ensembles for the historical period and for the future based on the four RCP emissions scenarios. The lower bound (17% of model projections are outside this bound) is given for the lowest emissions scenario and the upper bound for the highest emissions scenario. Data were smoothed using a 20-year sliding window, and rates are based on means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century are given for each RCP scenario. Colors in the background synthesize the ability of species to track climate through displacement. (B) Estimates of climate velocity were semi-quantitatively synthesized from seven studies using a diversity of analytical approaches and spatial resolutions. The three axes represent estimated climate velocities for mountainous areas (left), for global land area (center), and for regions that are flat or have high rates of climate change (right). (C) Rates of displacement for terrestrial plants, trees, mammals, birds, phytophagous insects, and freshwater mollusks. Each box represents ~95% of the estimates, and the bar is a qualitative estimate of the median. [Figure 4-6]

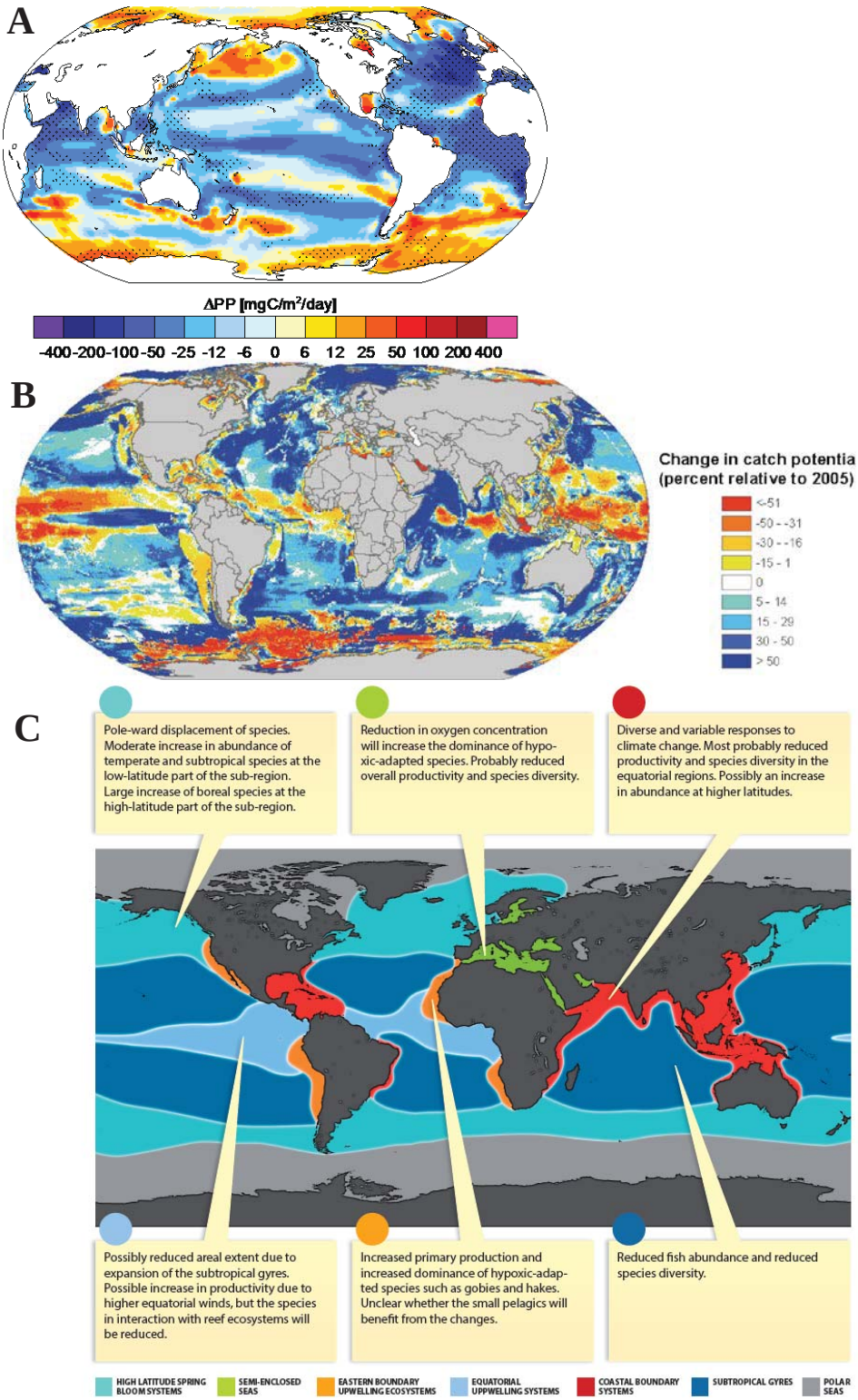


Figure TS.9: A) Multi-model mean changes of projected vertically-integrated net primary production (small and large phytoplankton). To indicate consistency in the sign of change, regions are stippled where all models (four in total) agree on the sign of change. Changes are annual means under the SRES A2 scenario (between RCP 6.0 and 8.5) for the period 2080 to 2099 relative to 1870 to 1889. B) A projection of maximum fisheries catch potential of 1000 species of exploited fishes and invertebrates from 2000 to 2050 under the SRES A1B scenario. C) Example of changes occurring within fisheries across the ocean. [Figures 6-14, 6-15, and 30-15]

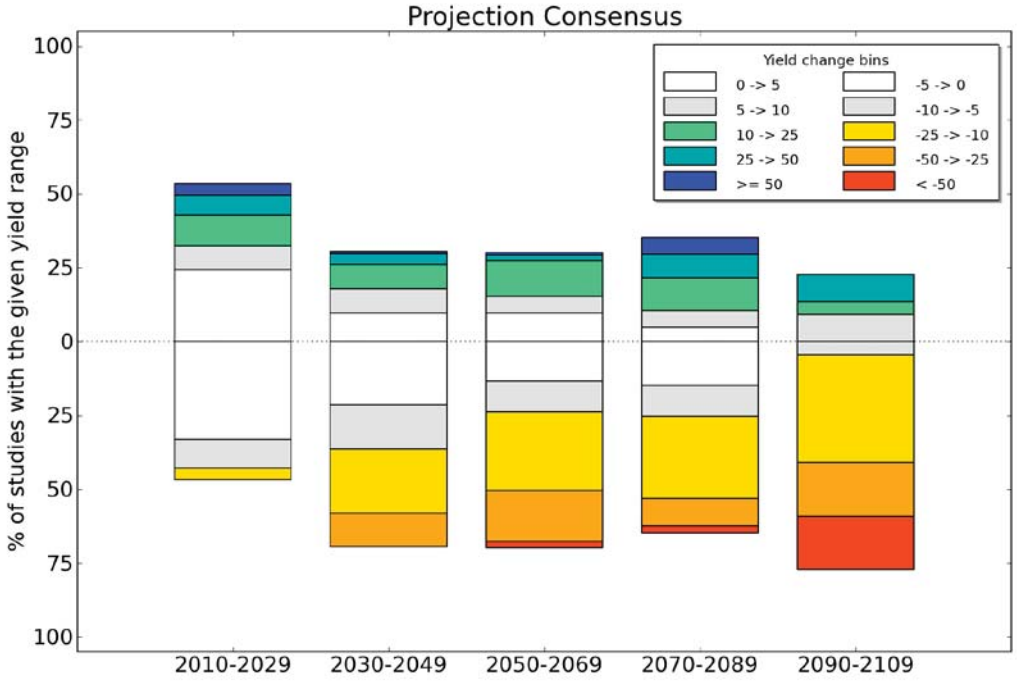


Figure TS.10: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colors denote percentage change in crop yield. Data are plotted according to the 20-year period in which the center point of the projection period falls. [Figure 7-6]

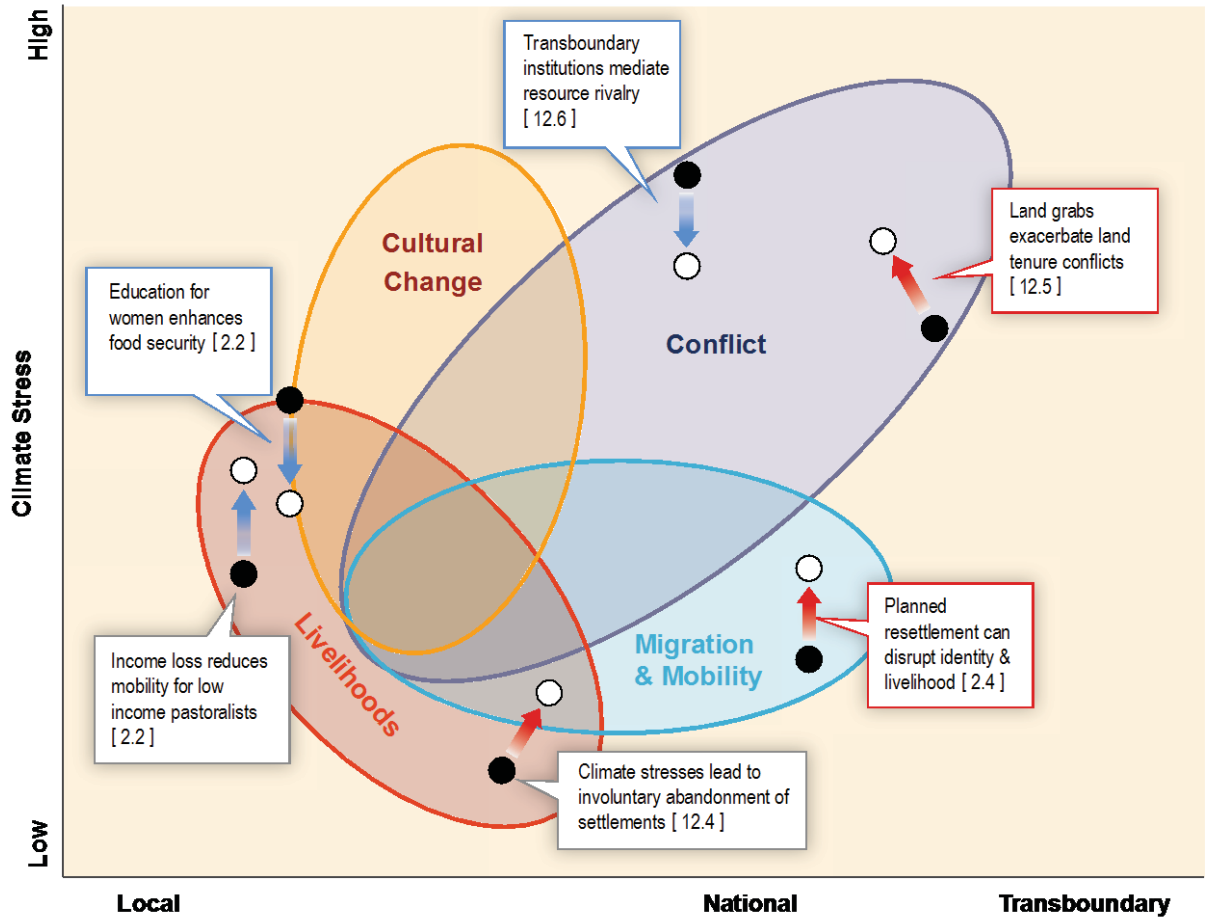


Figure TS.11: Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between elements. Examples of positive and negative changes in security associated with interventions indicated by arrows. [Figure 12-3]

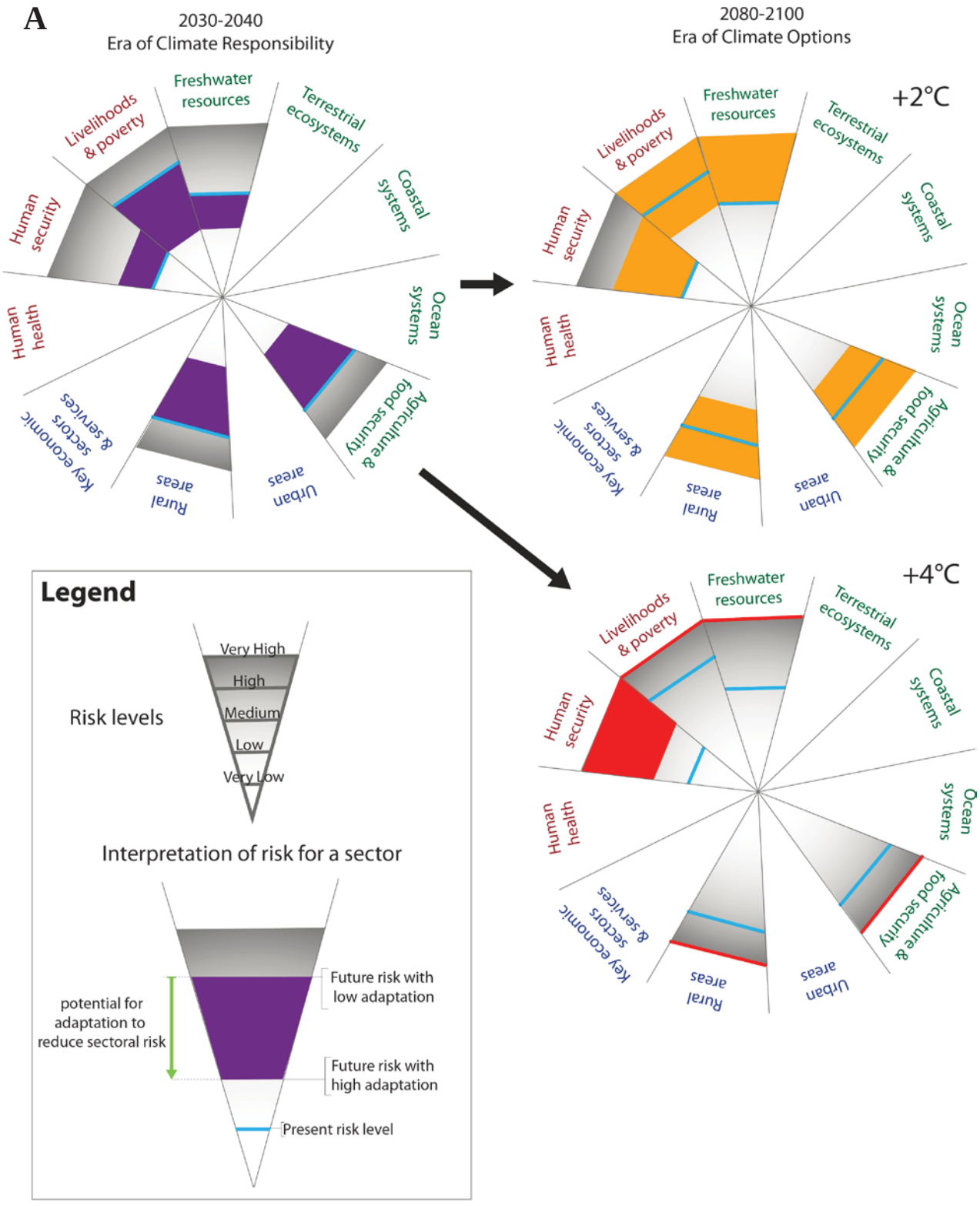
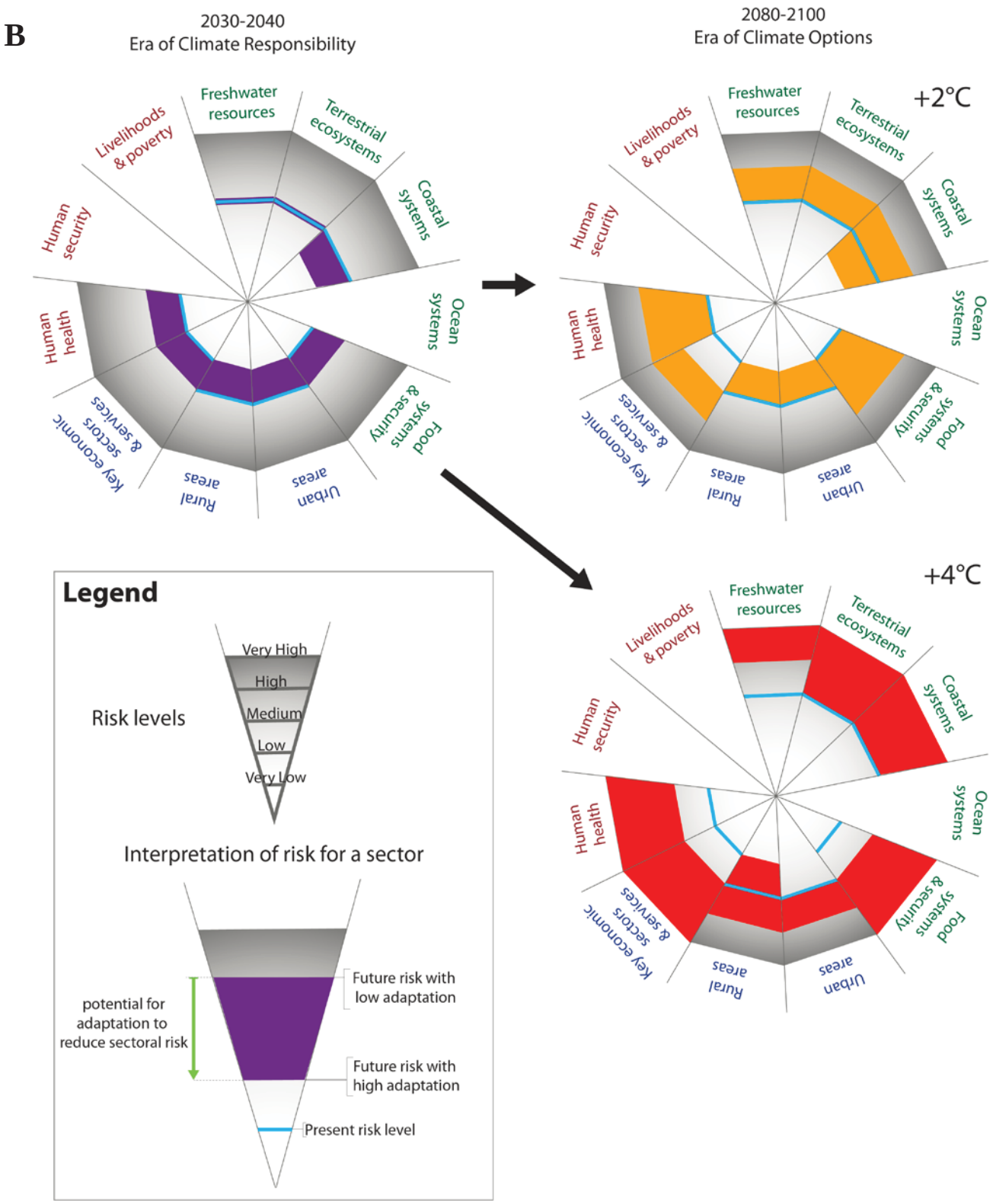


Figure TS.12: Estimated risk from climate change to selected sectors and systems in Africa (A), Europe (B), and North America (C), for different time frames (2030-2040 and 2080-2100), under two levels of global average warming above preindustrial (2°C and 4°C) and different assumptions about adaptation to manage these risks. Levels of risk and of adaptation are differentiated by colored shading, ranging from high adaptation to low adaptation. Estimated risks rely on expert judgments. The risk categories reflect the overall structure of Part A of the WGII AR5. [Figures 22-7 and 26-6]



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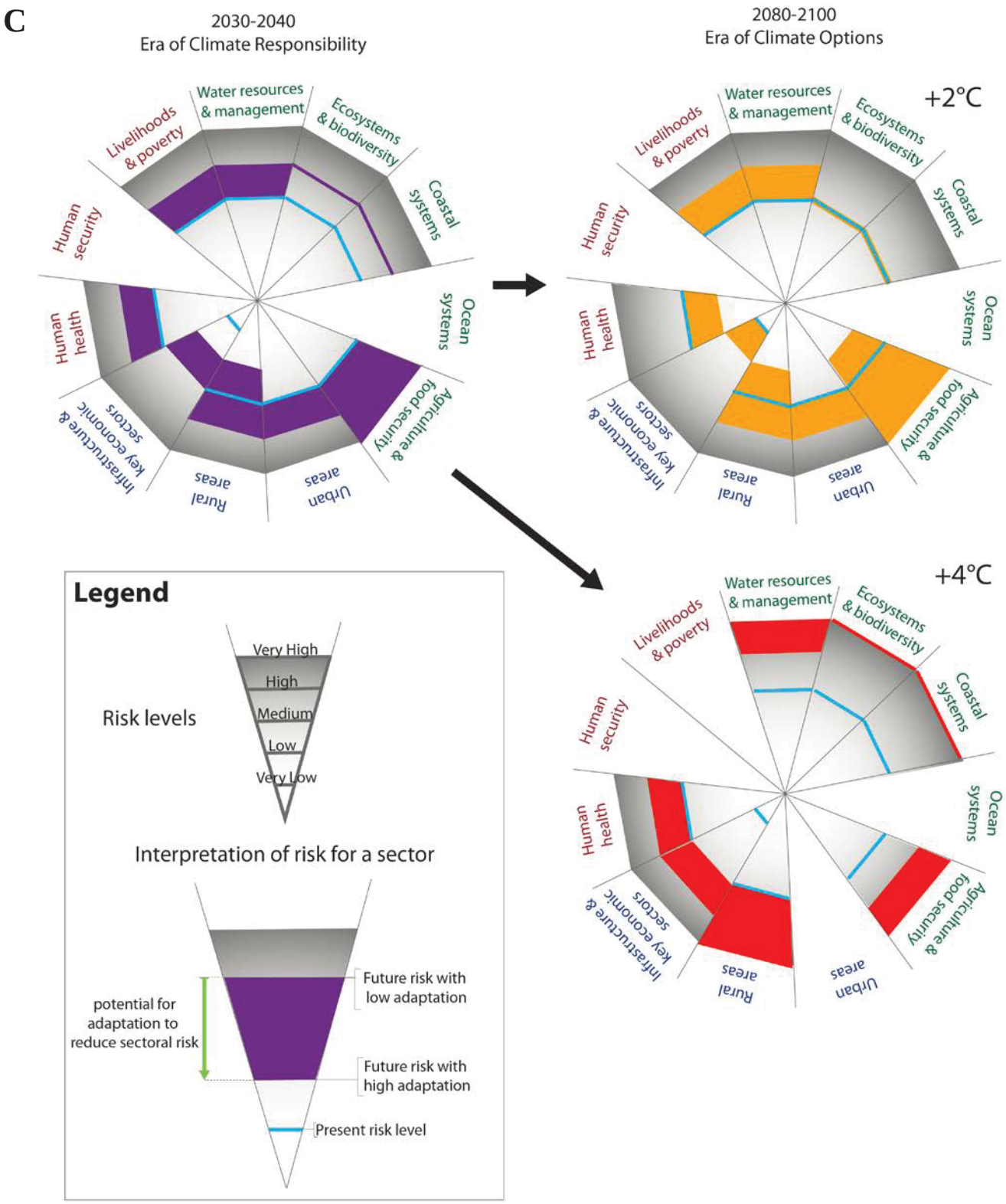


Figure TS.12: Estimated risk from climate change to selected sectors and systems in Africa (A), Europe (B), and North America (C), for different time frames (2030-2040 and 2080-2100), under two levels of global average warming above preindustrial (2°C and 4°C) and different assumptions about adaptation to manage these risks. Levels of risk and of adaptation are differentiated by colored shading, ranging from high adaptation to low adaptation. Estimated risks rely on expert judgments. The risk categories reflect the overall structure of Part A of the WGII AR5. [Figures 22-7 and 26-6]

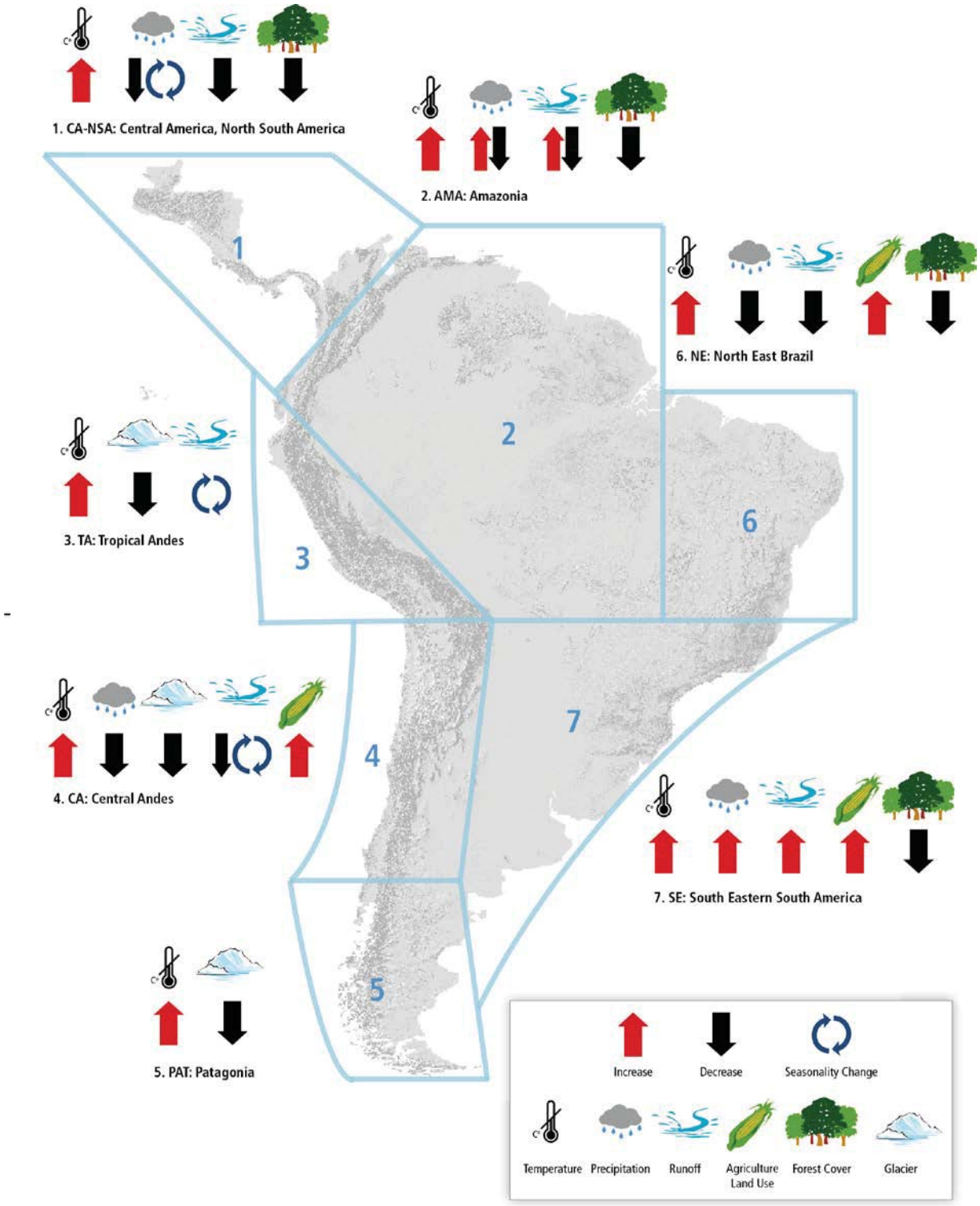


Figure TS.13: Summary of observed changes in climate and other environmental factors in representative regions of Central and South America. The boundaries of the regions in the map are conceptual (not precise geographic nor political) and follow those developed in SREX Figure 3-1. [Figure 27-7]

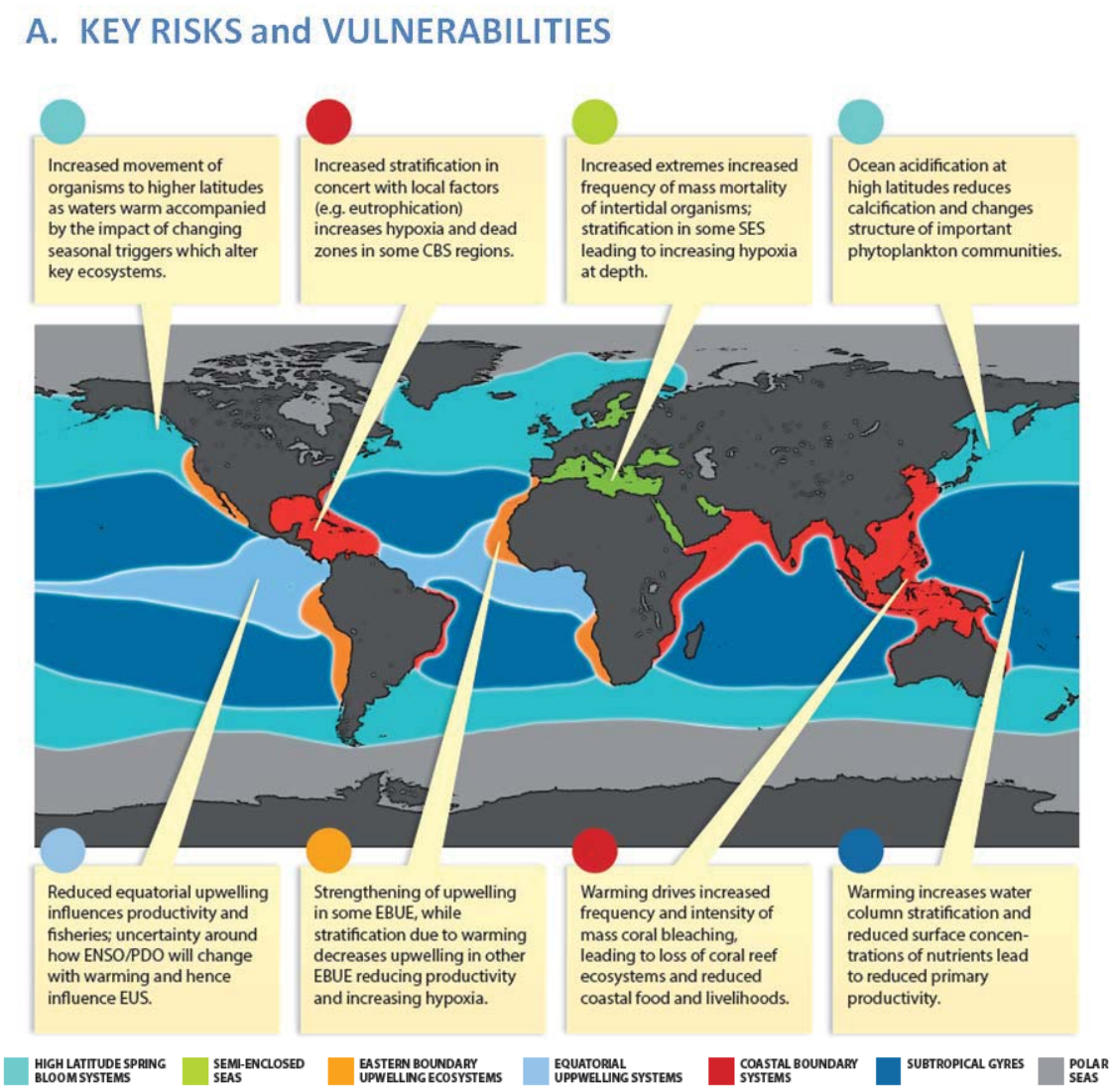


Figure TS.14: Summary of key risks and vulnerabilities associated with climate change on the world's ocean regions. [Figure 30-15]

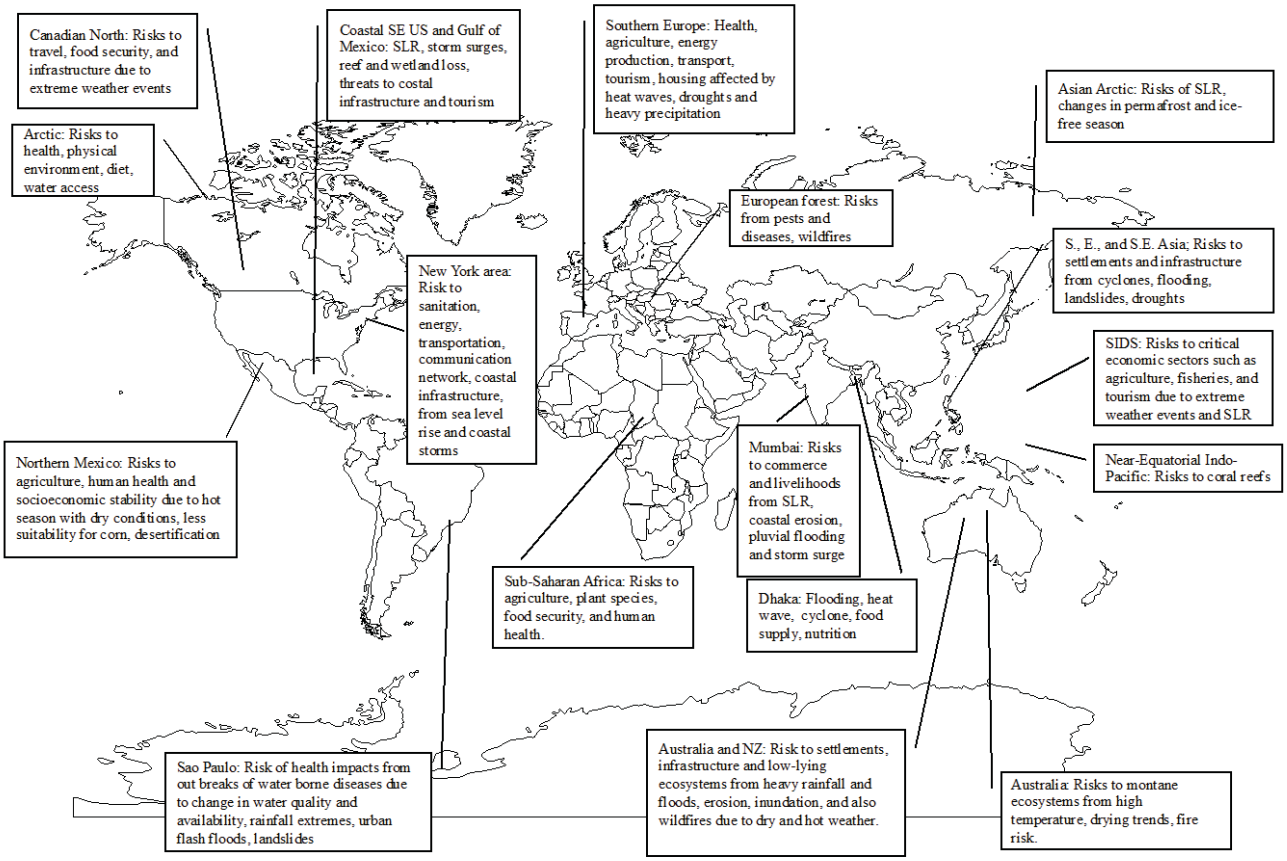
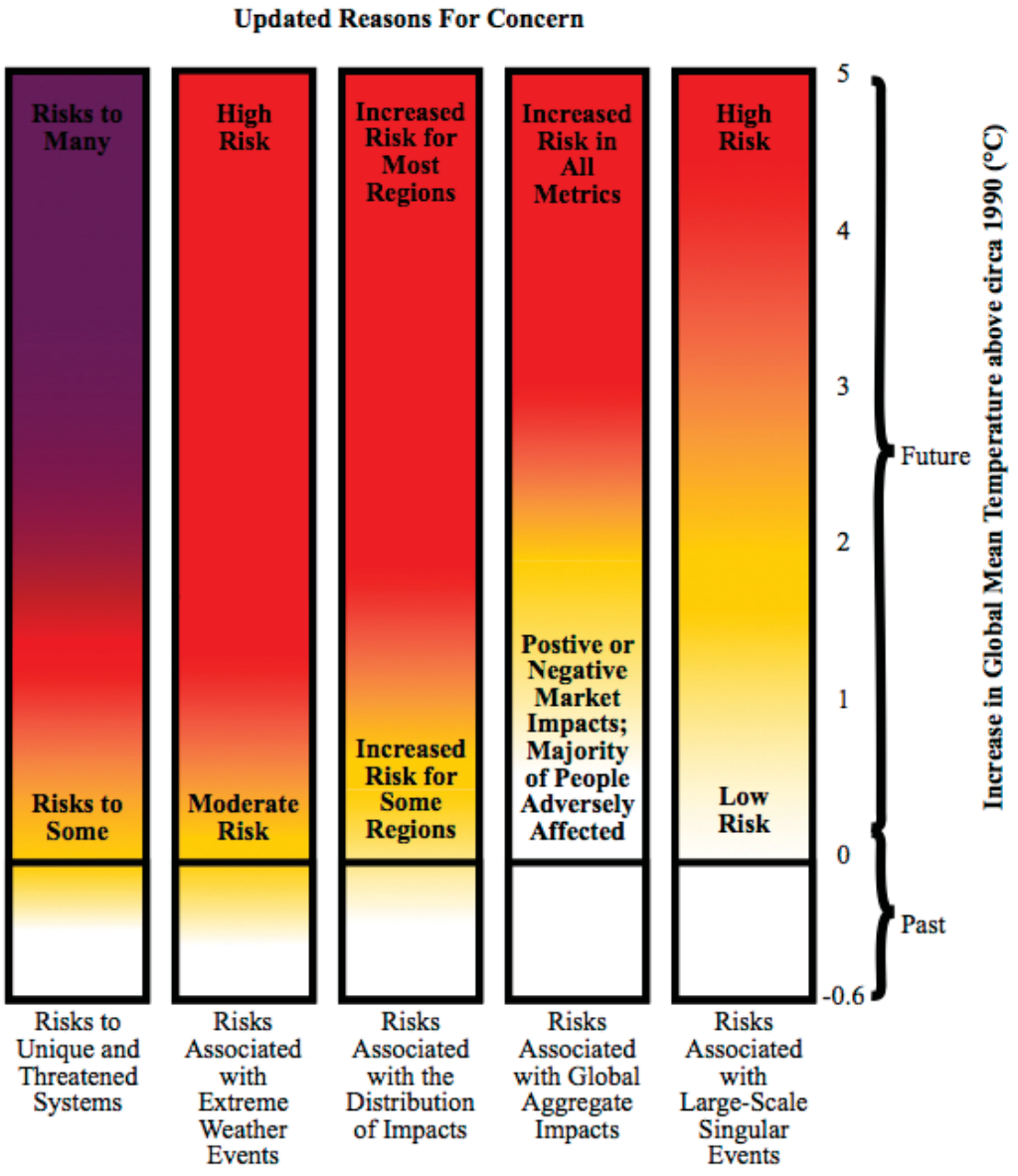
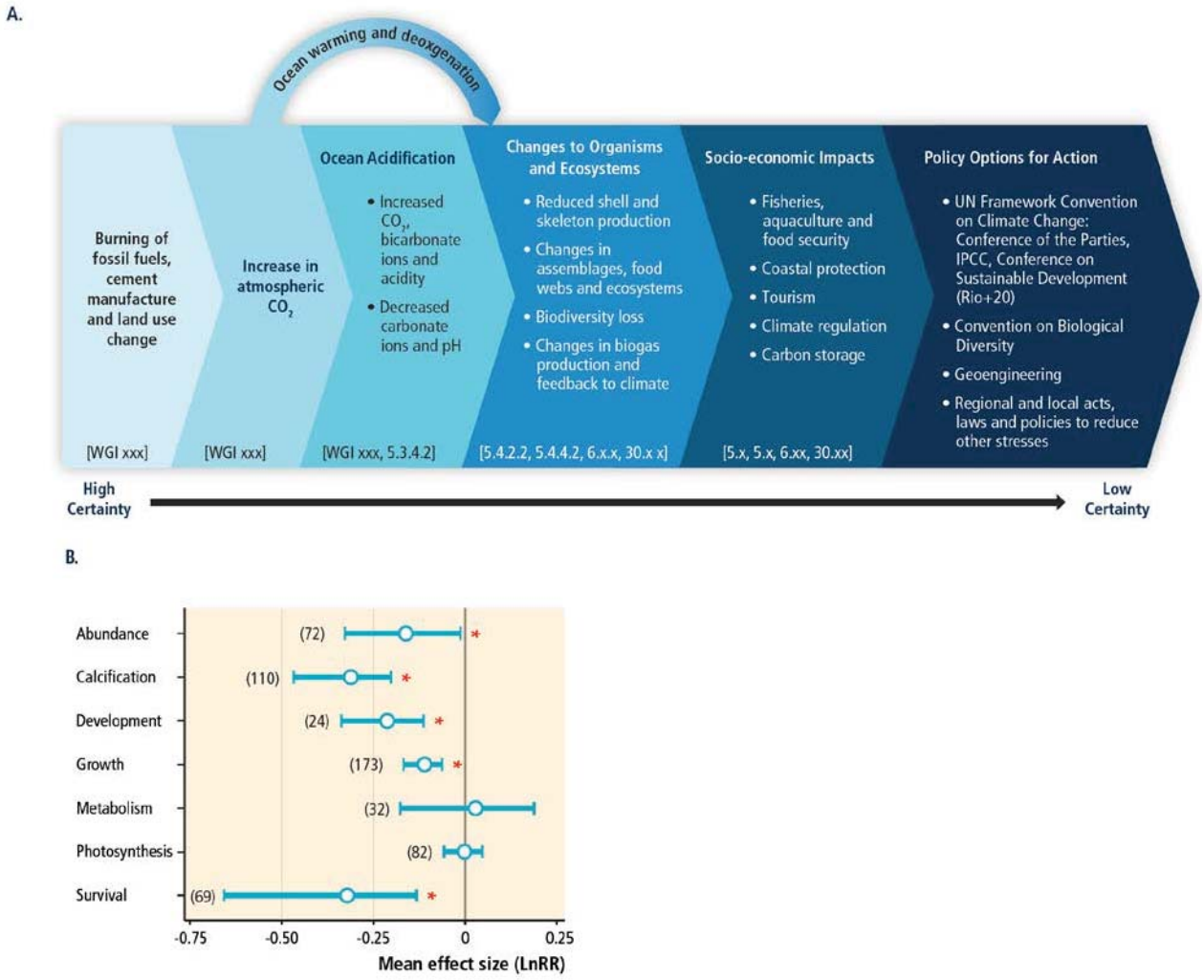


Figure TS.15: Some salient examples of multi-impacts hotspots identified in this assessment. [Figure 19-2]



Box TS.7 Figure 1: The dependence of risk associated with reasons for concern (RFCs) on the level of climate change, updated based on expert judgment in this assessment. The color scheme indicates the additional risk due to climate change (with white to purple indicating the lowest to highest level of risk, respectively). Purple color, introduced here for the first time, reflects the assessment that unique human and natural systems tend to have very limited adaptive capacity. [Figure 19-5]



Box TS.9 Figure 1: A) Overview of the chemical, biological, and socio-economic impacts of ocean acidification and of policy options. B) Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted. The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect. [Box CC-OA]

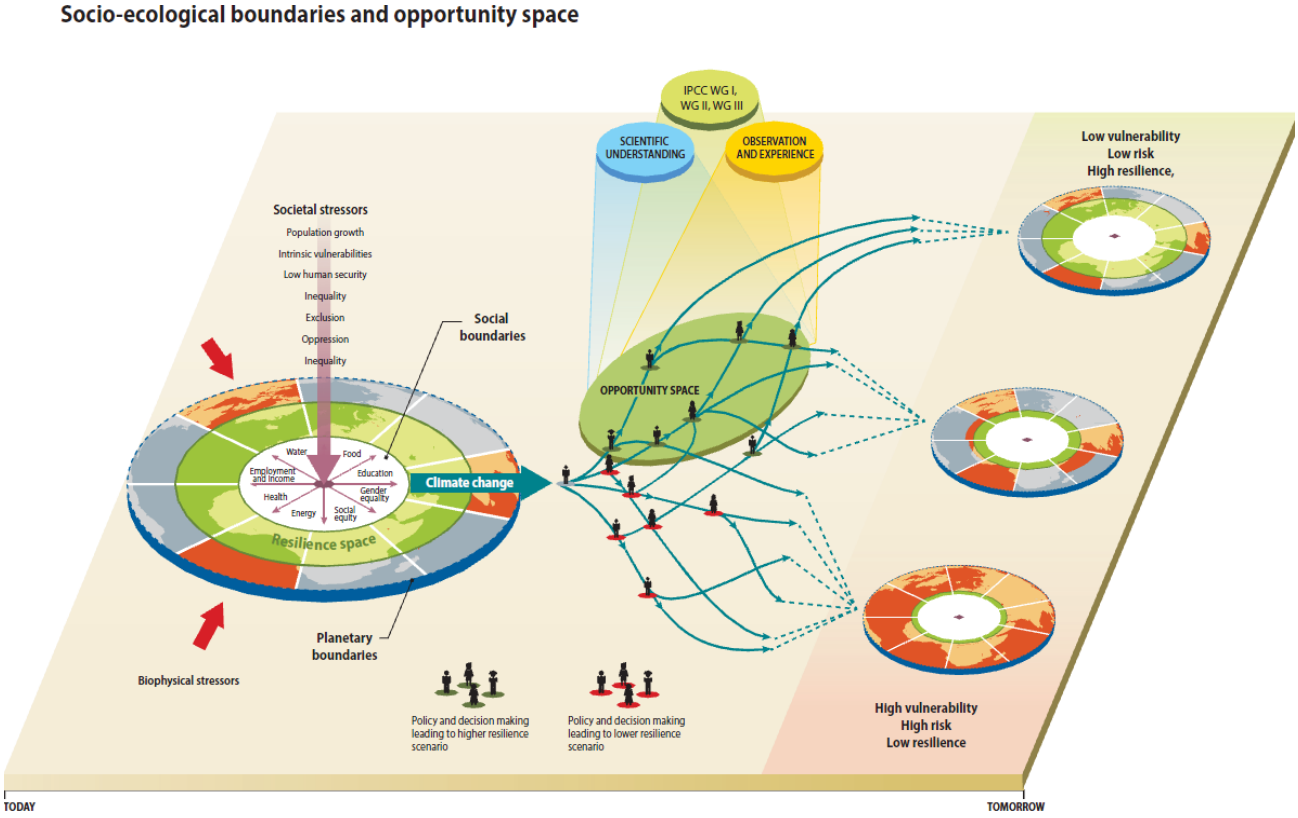
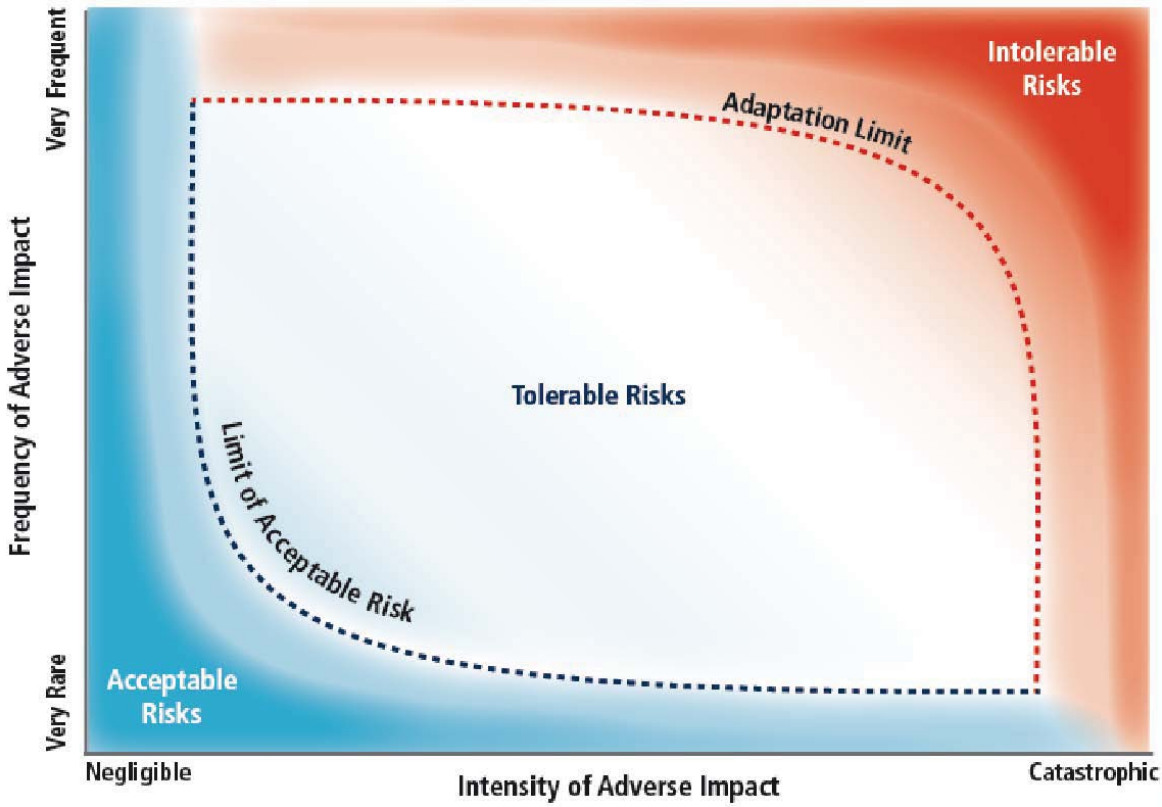


Figure TS.16: Conceptual framework for assessing interactions between biophysical and societal stressors that impact the resilience of natural and human systems today and in the future. Actions, including climate change adaptation and mitigation, taken in the opportunity space lead to a diverse range of pathways and outcomes—toward a future of high risk, high vulnerability, and low resilience space or toward a future of low risk, low vulnerability, and high resilience space. [Figure 1-7]



Box TS.10 Figure 1: Conceptual model of the determinants of acceptable, tolerable, and intolerable risks and their implications for limits to adaptation. [16.2, Figure 16-1]

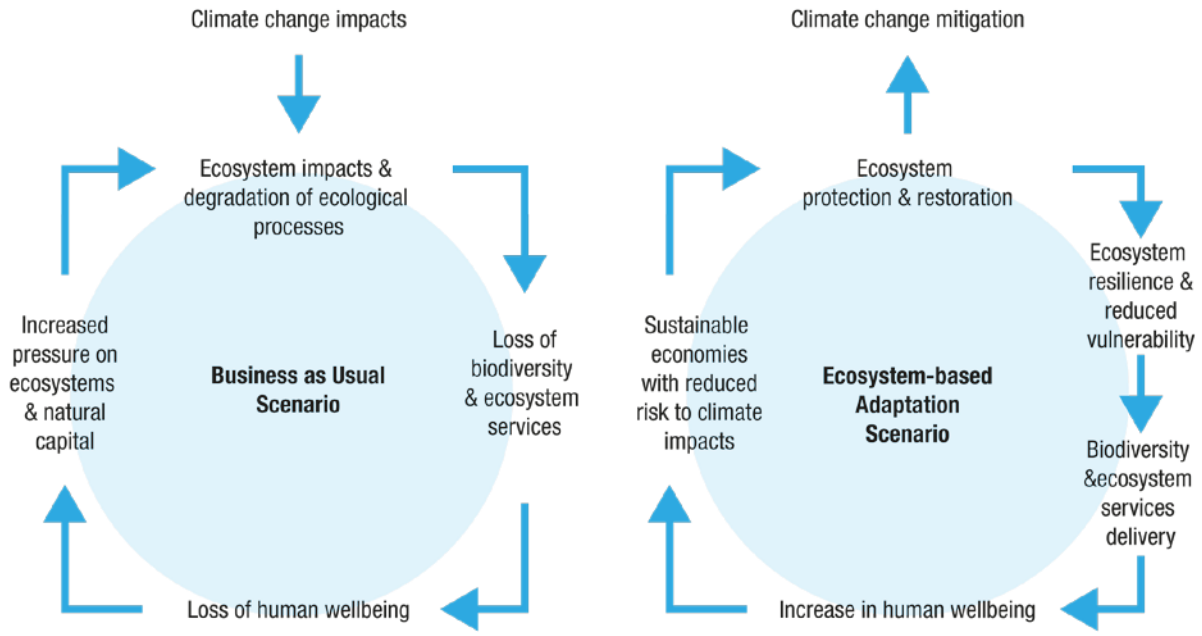


Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.

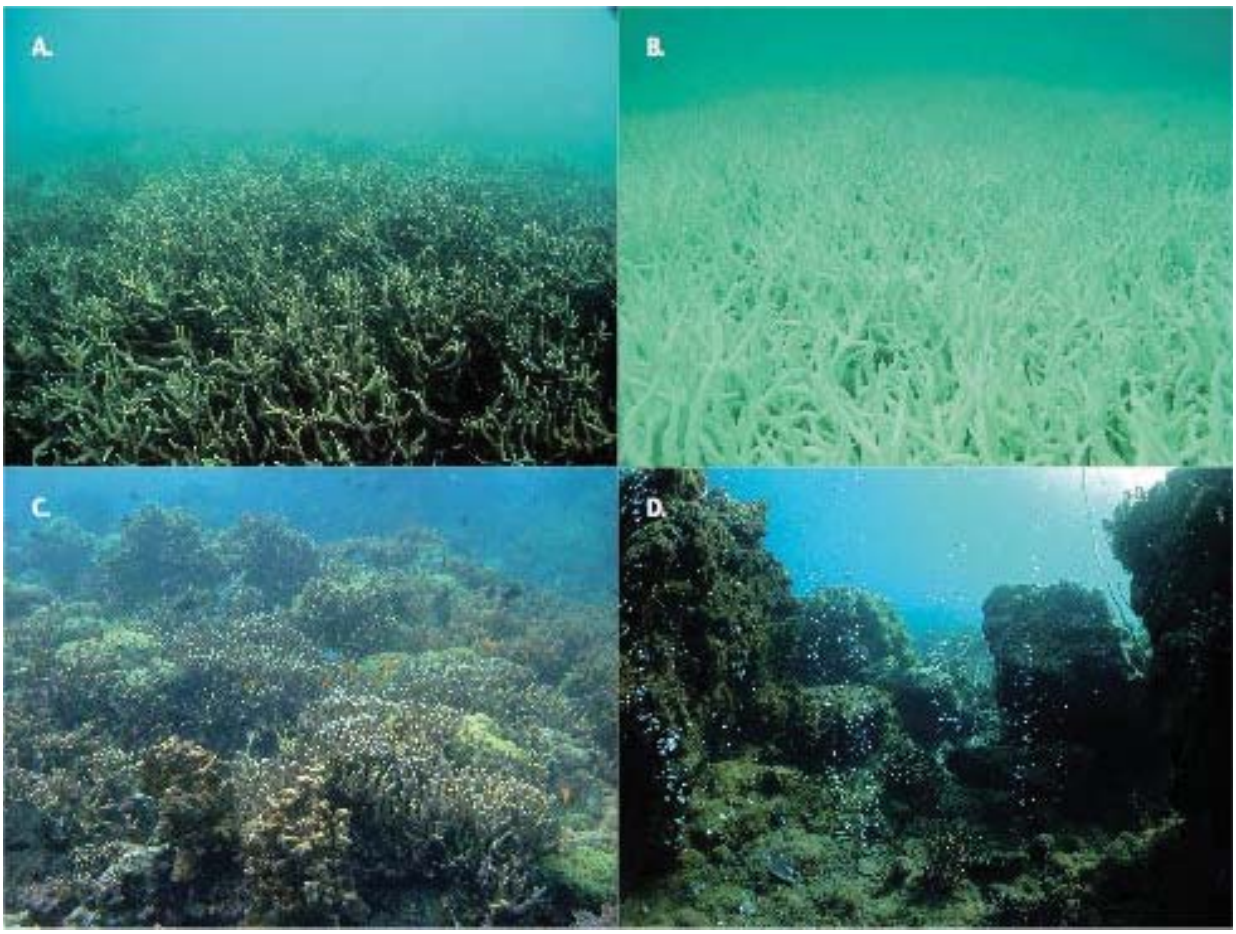


Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

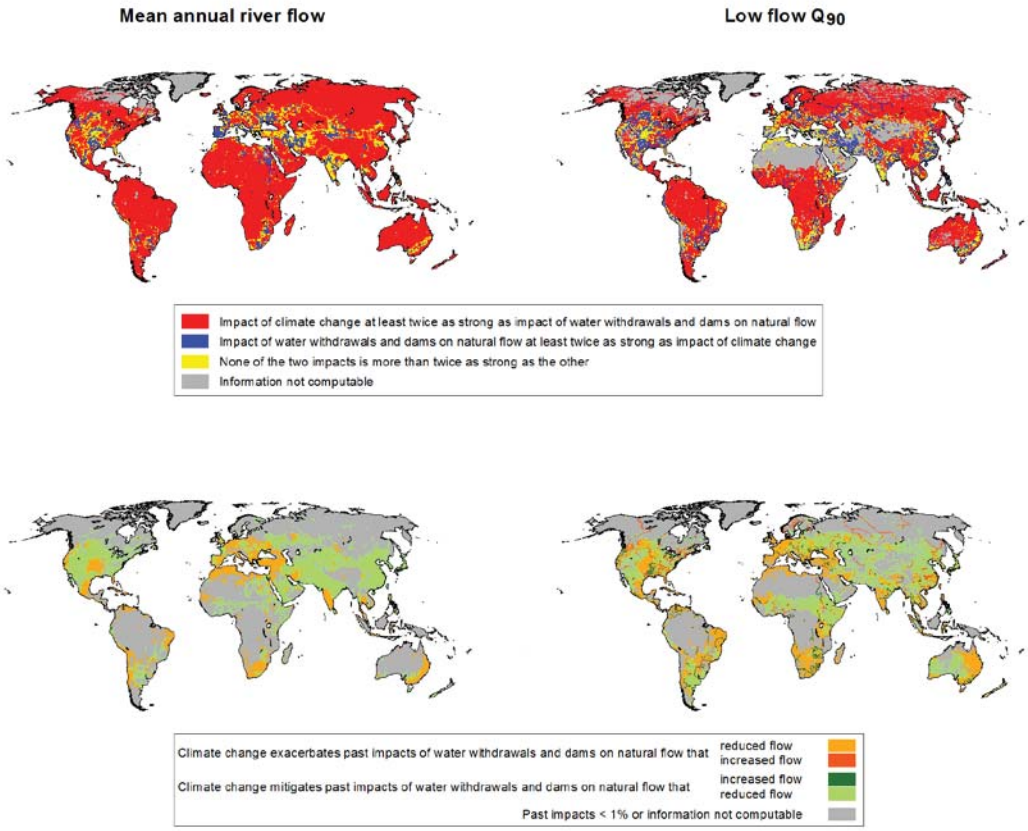


Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.

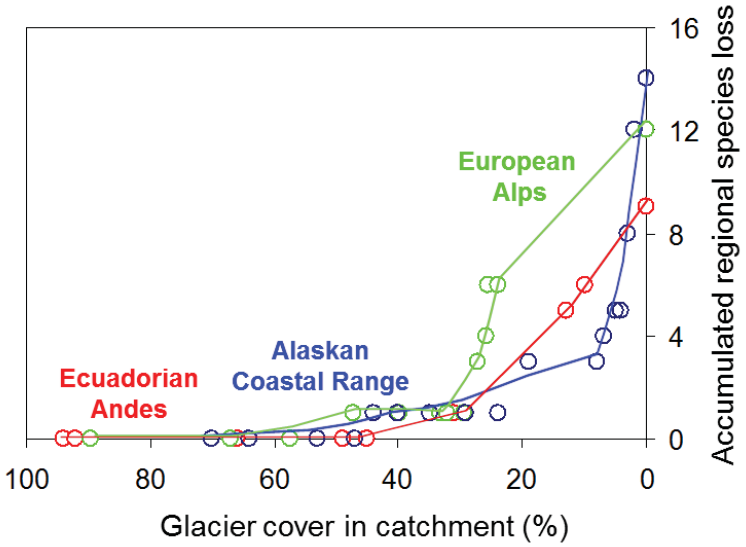


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

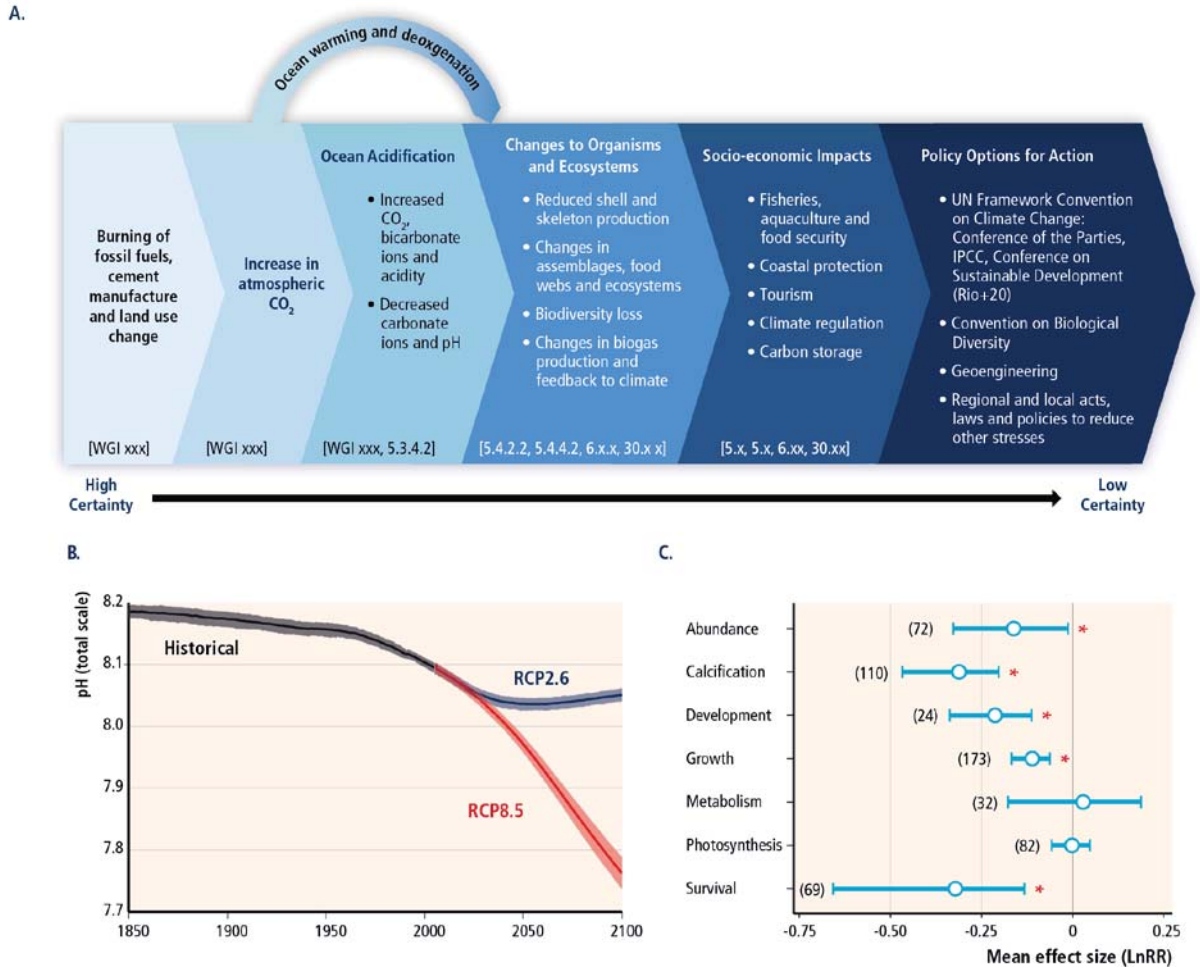


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

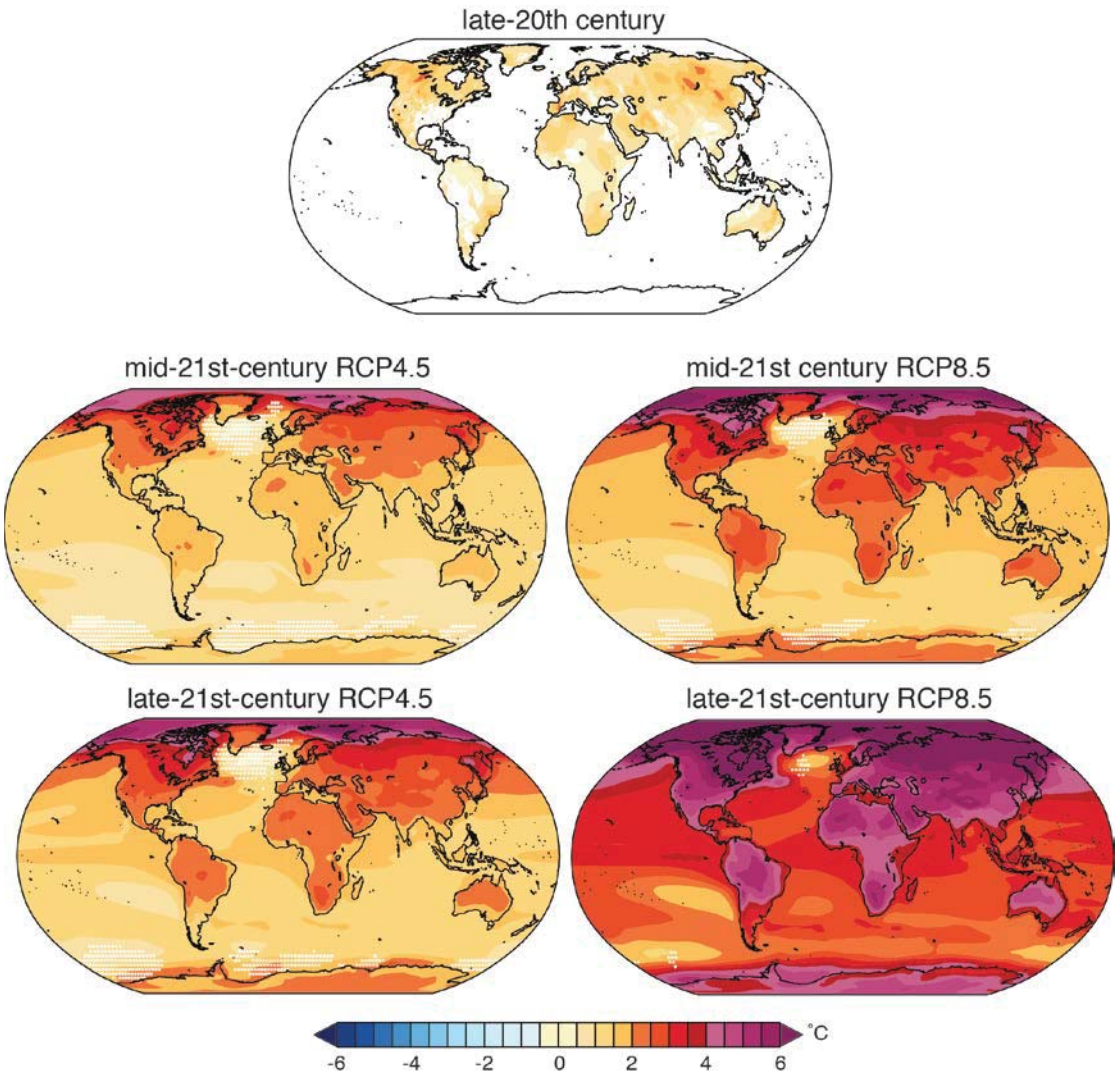


Figure RC-1: Change in annual temperature. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

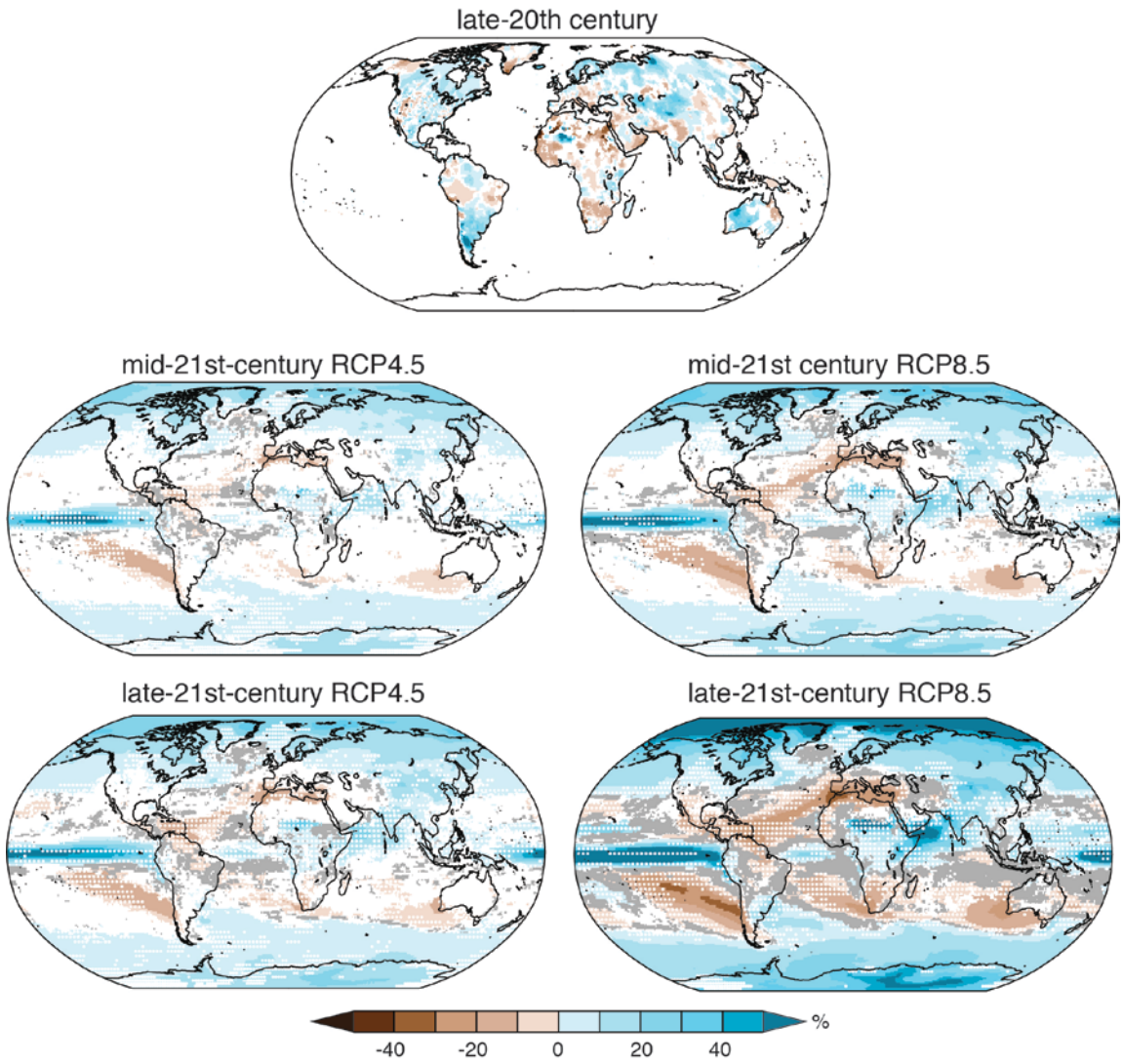


Figure RC-2: Change in annual precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

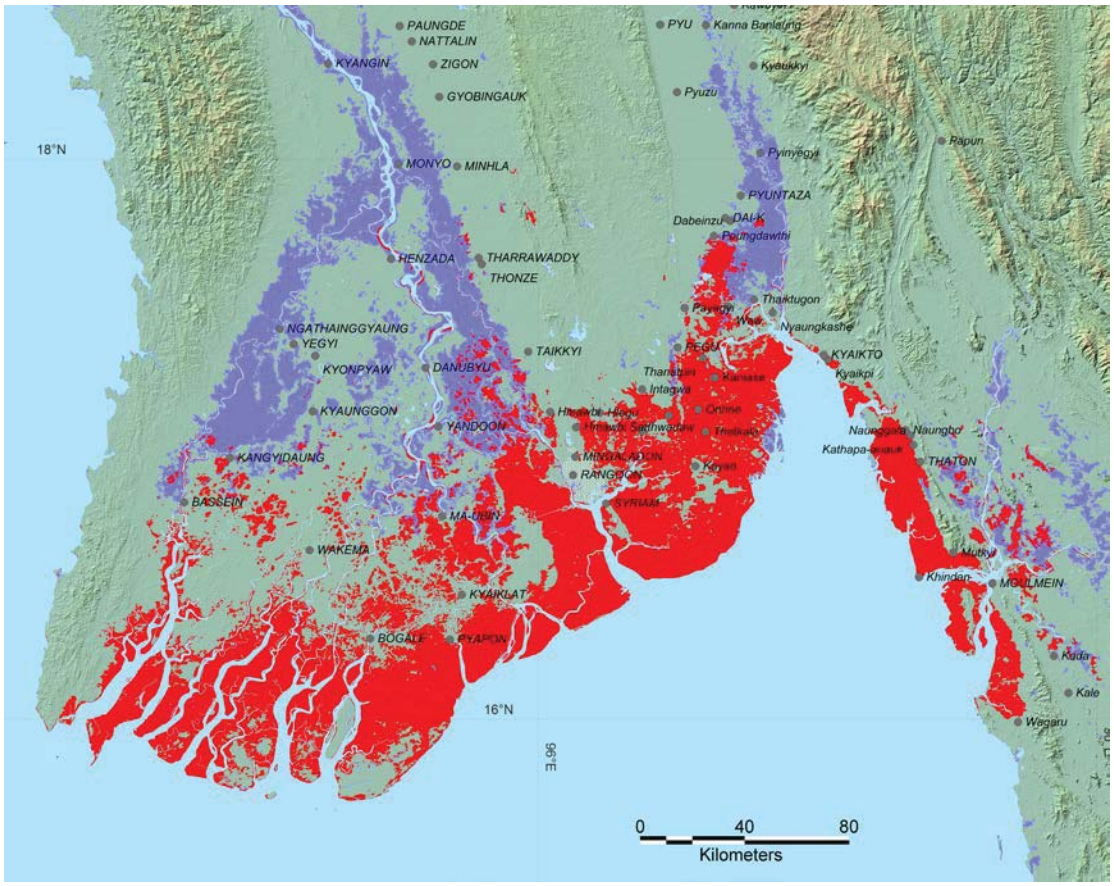


Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al.*, 2012).

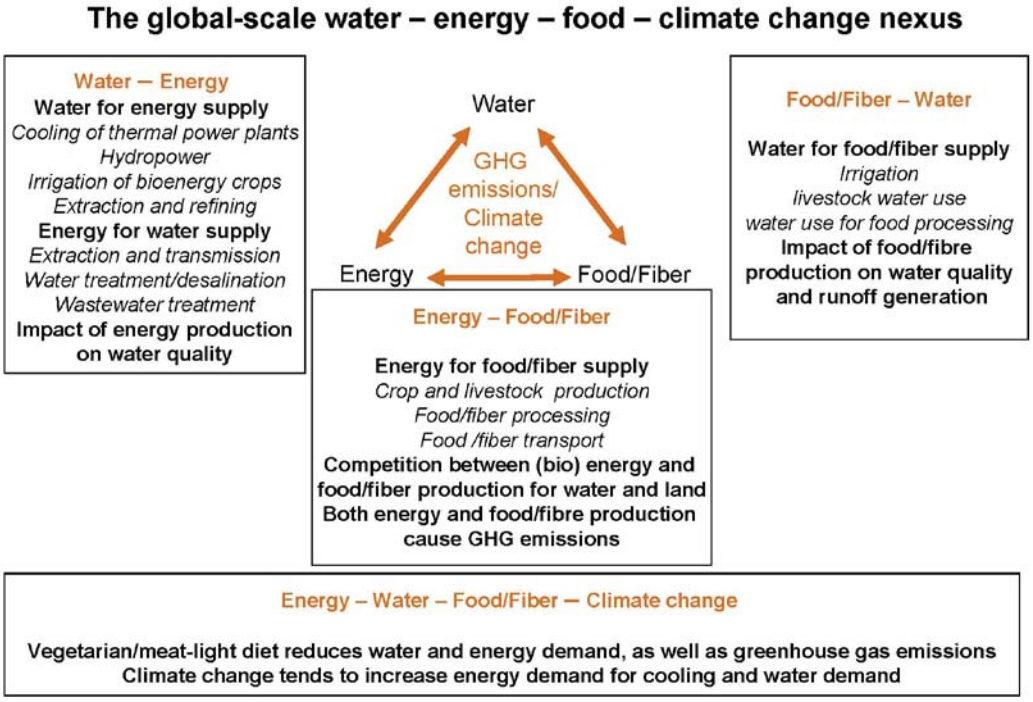


Figure WE-1: The water-energy-food nexus as related to climate change.

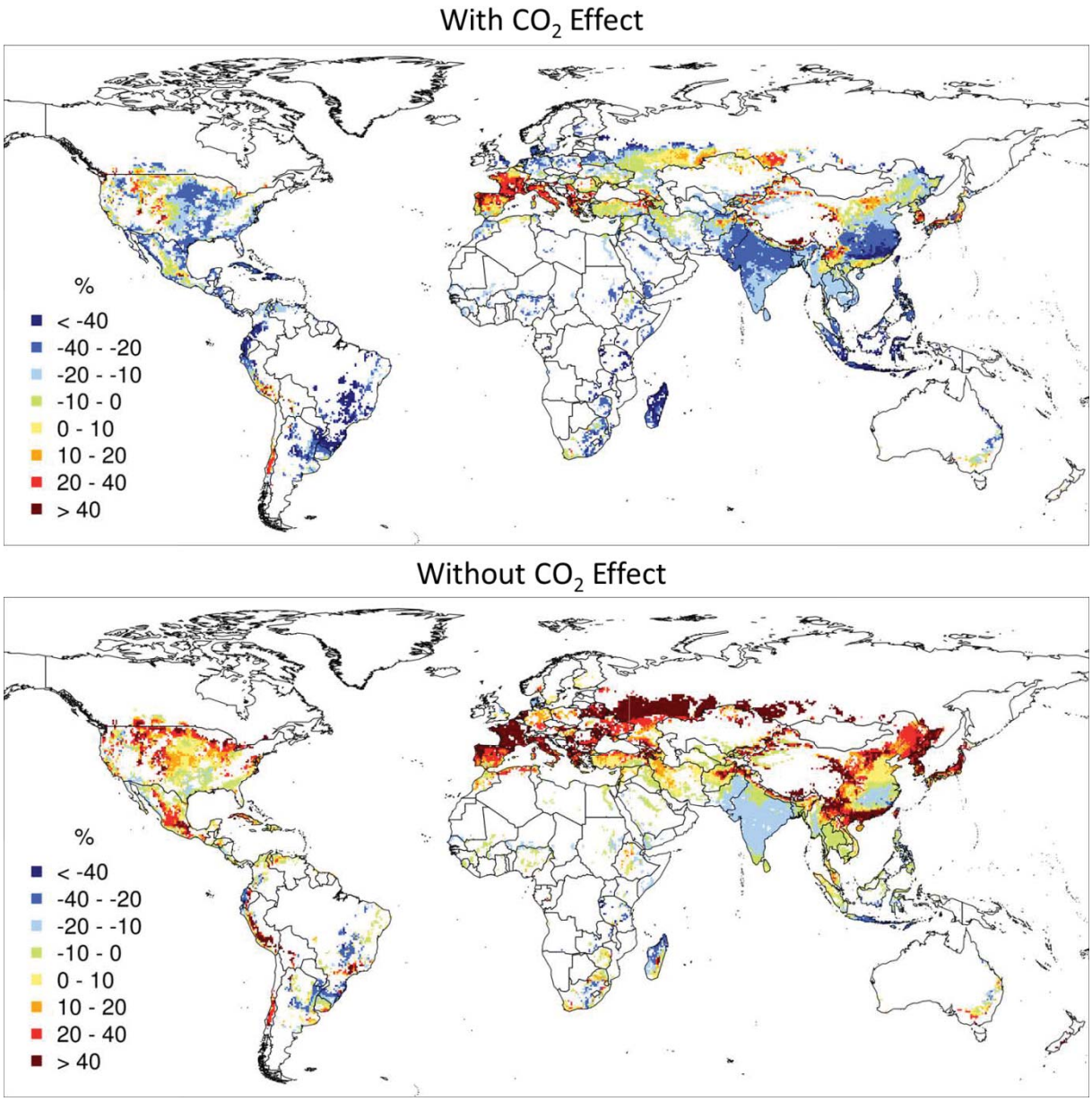


Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).

Chapter 1. Point of Departure

Coordinating Lead Authors
Virginia Burkett (USA), Avelino G. Suarez (Cuba)

Lead Authors
Marco Bindi (Italy), Cecilia Conde (Mexico), Rupa Mukerji (India), Michael Prather (USA), Asuncion St. Clair (Norway), Gary Yohe (USA)

Review Editors
Hervé Le Treut (France), Jean Palutikof (Australia)

Contributing Authors
Sarah Cornell (Sweden), Katharine Mach (USA), Michael D. Mastrandrea (USA), Jan Minx (Germany), Riccardo Pravettoni (Norway), Kristin Seyboth (USA), Christoph von Stechow (Germany)

Volunteer Chapter Scientist
Emmanuel Nyambod (Cameroon)

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Frequently Asked Questions

1.1: What is the information basis for the assessment and how has it changed since the last IPCC report?
1.2: How has our understanding of the interface between human, natural, and climate systems expanded since the 2007 IPCC Assessment?
1.3: How is the state of scientific understanding communicated in this report?

References

Executive Summary

The literature available for assessing climate change impacts, adaptation, and vulnerability has more than doubled since 2005 (*very high confidence*). The diversity of the topics and regions covered by the literature has similarly expanded, as well as the geographic distribution of the authors contributing to the knowledge base for climate change assessments. Production of climate change literature has increased in the developing countries, although their institutions lag those in developed countries regarding access to and production of climate change literature. The unequal distribution of literature, which is influenced by factors such as scientific funding and capacity building, presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. [1.1.1, Figure 1-1]

The evolution of the IPCC assessments of impacts, adaptation, and vulnerability indicates an increasing emphasis on humans, their role in managing resources and natural systems, and the societal impacts of climate change (*very high confidence*). The expanded focus on societal impacts and responses is evident in the composition of the IPCC author teams, the literature assessed, and the content of the IPCC assessment reports. Three important characteristics in the evolution of the Working Group 2 assessment reports are an increasing attention to: (i) Adaptation limits and transformation in societal and natural systems; (ii) Synergies between multiple variables and factors that affect sustainable development, including risk management, and (iii) Institutional, social, cultural, and value-related issues. [1.1, 1.2]

Adaptation has emerged as a central area of work in climate change research, in country level planning and in the implementation of climate change strategies *(high confidence).* The body of literature shows an increased focus on the capitalizing on adaptation opportunities and the interrelations between adaptation, mitigation and alternative sustainable pathways. In spite of the uncertainty of future impacts and adaptation, the literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection and disaster risk reduction and management. [1.1.4]

The treatment and communication of uncertainties in IPCC reports have evolved over time, reflecting iterative learning and more coherent guidance across all Working Groups *(high confidence).* An integral feature of IPCC reports is communicating the strength and uncertainties in the scientific understanding underlying assessment findings. In Working Group II, the use of calibrated language began in the SAR, where most chapters used qualitative levels of confidence for their Executive Summary findings. Based on experience, guidance notes were developed for subsequent AR. The AR5 Guidance Note continues to emphasize a theme from all three guidance documents to date: the importance of clearly linking each key finding and corresponding assignment of calibrated uncertainty language to associated chapter text, as part of the traceable account of the author team's evaluation of evidence and agreement supporting that finding. [1.1.2.2, Box 1-1]

Impacts assessed in this report are based on a combination of AR4 climate models (CMIP3) using SRES scenarios and new AR5 climate models (CMIP5, completed in 2011-12) using the new Representative Concentration Pathway (RCP) scenarios. The RCPs span the range of SRES scenarios for long-lived greenhouse gases, but they have a narrow range and fall at or below the lowest SRES in terms of emissions of ozone and aerosol precursors and related pollutants *(high confidence).* The IPCC has created and used emission scenarios to project future climate since the FAR, and most recently the SRES scenarios were used in the TAR and AR4. With AR5, the new RCP scenarios present both emissions and greenhouse gas concentration pathways, and

corresponding shared socio-economic pathways have also been developed. The 4 RCPs assume different levels of mitigation, leading to 21st century radiative forcing levels of 2.6, 4.5, 6.0 and 8.5 W m^{-2} (See WGI Chapters 1, 6, 11, 12). All RCPs project a rapid decline in short-lived pollutants and land-use change by 2050, almost independent of fossil-fuel use and population, while other published scenarios indicate a less rapid decline in aerosol precursors**.** [1.1.3]

1.1. The Setting

This chapter describes the information basis for the Fifth Assessment Report (AR5) of IPCC Working Group II and the rationale for its organization. As the initial point of departure from the prior IPCC WGII assessments, the chapter begins with an analysis of how the literature for the assessment has developed through time and proceeds with an overview of how the framing and content of the Working Group II reports have changed since the first IPCC report was published in 1990. The future climate scenarios that have been used by the scientific community to explore the potential consequences of climate change have marked important transitions over the past five years; this chapter describes the evolution of these scenarios and the methods used to communicate scientific uncertainty in IPCC assessments. The chapter provides a summary of the most relevant key findings from the IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (IPCC, 2011a), the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), and the IPCC Working Group I (*The Physical Science Basis*) and Working Group III (*Mitigation of Climate Change*) contributions to AR5. Collectively these recent reports, new scenarios, and other advancements in climate change science set the stage for an assessment of impacts, adaptation and vulnerability that could potentially overcome many of the limitations identified in the IPCC Fourth Assessment Report (AR4), particularly with respect to the human dimensions of climate change.

The IPCC has published four impact assessment reports (WGII) of the state of knowledge of climate change in 1990, 1995, 2001 and 2007. The critical review and synthesis of the scientific literature published since 2007 has required an expanded multidisciplinary approach that, in general, has more focused more heavily on societal impacts and responses. This includes analysis on how aggregate impacts are the result of coupled socio-ecological systems, and the rapid emergence of research on adaptation and vulnerability. The chapter shows an increased concern with how societal change evolves and the role of transformative thinking and action to achieve sustainability, a dynamic process that helps guarantee the persistence of natural and human systems.

In addition to the knowledge gaps in earlier Reports, point of departure in this chapter refers to a combination of the status of the biophysical planetary boundaries and the existing social boundaries on which climate impacts occur. These social boundaries include poverty and inequality, low levels of human development, and lack of access to basic needs and energy by a large part of an increasing global population interacting creating and reaction to climate change (see 1.1.4 and Figure 1-7).

The IPCC WGII Fifth Assessment Report (AR5) differs from the prior assessments primarily in the expanded outline and diversity of content that stems directly from the growth of the scientific basis for the assessment. The publication of the WGII contribution to AR5 in two volumes (Part A. Global and Sectoral Aspects and Part B. Regional Aspects) has permitted the presentation of more detailed regional analyses and an expanded coverage of the human dimensions (such as adaption) described above. For the IPCC Fifth Assessment, the contributions of Working Group I (Climate Change 2013: The Physical Science Basis) were finalized approximately six months in advance of the Working Group II contributions, allowing the authors of the latter more time to evaluate and include where possible the findings of Working Group I AR5 in the context of impacts, adaptation and vulnerability.

1.1.1. Development of the Science Basis for the Assessment

The volume of literature available for assessing climate change impacts, adaptation and vulnerability (CCIAV) has grown significantly over the past two decades (Figure 1-1a). A bibliometric analysis of reports produced with two bibliographic search tools (Scopus and ISI Web of Knowledge) indicates that fewer than 800 articles in journals,

books, and conference proceedings were published in English on the topic of "climate change" between 1970 and 1990. Since then, the literature published on the topic has increased almost 100-fold, with a total of 73,039 articles published from 1990 through 2010. Since 1990 the international distribution of scientists contributing to the climate change literature has expanded from Europe and North America to Asia and Australasia. Literature from scientists affiliated with institutions in Africa and Central and South America comprised approximately 6% of the literature published on the topic of climate change during 2001-2010 (Figure 1-1b). The proportion of literature focusing on individual countries within IPCC regions has also broadened, particularly for Asia, over the past 3 decades (Figure 1-1c). This brief chronicle does not differentiate across the various "sub-categories" of the climate literature or claim to be comprehensive in terms of literature produced in languages other than English. For example, disparities of the geographic coverage of the climate change literature on the capacity for adaptation or the assessment of impacts and vulnerability have not been assessed.

[INSERT FIGURE 1-1 HERE
Figure 1-1: Results of English literature search using the Scopus bibliographic database from Reed Elsevier Publishers. (a) Annual global output of publications on climate change and related topics: impacts, adaptation, human health, and costs (1970-2010). (b) Country affiliation of authors of climate change publications summed for IPCC regions for three time periods: 1981-1990, 1991-2000, and 2001-2010, with total number during the period 2001-2010. (c) Results of literature searches for climate change publications with individual countries mentioned in publication title, abstract or key words, summed for all countries by geographic region. The following individuals conducted the literature searches: Valentin Przyluski (French), Huang Huanping (Chinese), and Peter Zavialov and Vasily Kokore (Russian), and Saúl Armendáriz Sánchez (Spanish). (d) Number of publications in five languages that include the words "climate change" and "climate change" plus "adaptation", "impacts" and "cost" (translated) in the title, abstract or key words during the three time periods.]

Growth in both the total volume of literature about climate change and the percentage of that literature devoted to impacts and adaptation has influenced the depth and scope of assessment reports produced by Working Group II of the IPCC. A doubling of the total number of publications on the topic of climate change impacts between 2005 and 2010 and on the topic climate change adaptation between 2008 and 2010 has enabled substantial advances in the assessment of the full range of impacts, adaptation and vulnerability (Figure 1-1a). The unequal distribution of literature, however, presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. The geographical and topical distribution of literature is influenced by factors such as the availability of funding for scientific research, level of capacity building, regional experience with climate-related disasters, and the availability of long-term observational records.

Literature published on the topic of climate change during 1970-1990 focused primarily on changes in the physical climate system and how these changes affected other aspects of the Earth's physical environment. The Scopus database indicates that literature began to surface at the rate of more than 100 articles per year on the topic of climate change "impacts" in 1991. The rate of publication of at least 100 articles per year on the topics of climate change "adaptation" and societal "cost" began in 2003. The proportion of the literature on the topic of "climate change" published in social science journals increased from 6% to 9% from the 1970s-1980s to the 1990s-2000s. The proportion of the literature on the topic of "climate change" appearing in engineering journals has not changed appreciably over the past four decades, but there was a significant increase in the proportion of literature relating to climate change in the biological and agricultural science literature. The themes covered by literature on vulnerability to climate change have also expanded to issues of ethics, equity, and sustainable development.

While authors continue to publish primarily in English, literature published on the topic of "climate change" in other languages have also expanded. Literature searches in Chinese, French, Russian and Spanish revealed roughly a 4-fold or greater increase in literature published on the topic of "climate change" in each language during the past two decades (Figure 1-1d). Scientists from many countries tend to publish their work in English, as indicated by comparing the regional analysis and country affiliation of authors in Figure 1-1 with the results of the literature searches in the other 5 languages. This process of "scientific internationalism", which primarily means a shift to English as a language of scientific communication, has been described as a growing trend among Russian (Kirchik, Gingras, and Ladviere, 2012), Spanish (Alcaide, Zurián, and Benavent, 2012), and French (Gingras and Mosbah-Natanson, 2010) researchers.

1.1.2. Evolution of the WGII Assessment Reports and Treatment of Uncertainty

1.1.2.1. Framing and Outlines of WGII Assessment Reports

The framing and contents of the IPCC WGII assessments have evolved since the First Assessment Report (FAR, 1990) as summarized in Figure 1-2. Three important characteristics of this evolution are: (i) extended range and coupling of variables that impact a sustainable future; (ii) an increasing focus on human beings (managing resources and natural systems, the societal impacts of climate change); and (iii) participation of more social and human dimensions scholars as authors and reviewers. The continuing focus of WGII on impacts, adaptation and vulnerability extends the assessment challenges from the physical, ecological and economic systems to institutional, social and cultural issues. Effectively, WGII now focuses on understanding the interactions between the natural climate system and human society, adding to the emphasis of earlier assessments on sectoral and regional biogeophysical impacts of climate change. This assessment contributes to a better understanding of the likelihood of certain development paths, a key uncertainty in climate projections.

[INSERT FIGURE 1-2 HERE
Figure 1-2: Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The First Assessment Report (FAR, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change, but for the Second Assessment Report (SAR, 1996) the WGII contribution included mitigation and adaptation with the impact assessment. With the TAR (2001) and subsequent assessments, IPCC Working Group III has assessed the options and potential for climate change mitigation. Since the TAR, WG II has focused on impacts, adaptation and vulnerability with an expanded effort on the regional scale.]

The WGII FAR (296 pages) was organized into six major sectors: agriculture & forestry, terrestrial ecosystems, water resources, human settlements, and oceans & coastal zones. The report focused on the anticipated climate changes for a doubling of CO_2. The FAR SPM highlights the coupling of anthropogenic non-climate stresses with climate variability and greenhouse-gas-driven climate change. Given the state of the science in 1990, it is understandably qualitative on some topics (e.g., global agricultural potential may either increase or decrease; major health impacts are possible), but more quantitative on large-scale climate impacts (e.g., climatic zones shift poleward by 100s km; alpine and montane regions are most at risk for habitat and species loss). Health impacts were vague, emphasizing ozone depletion and UV-B damage. The IPCC WGII 1992 Supplementary Report followed with four assigned topics (regional climate change; energy; agriculture and forestry; sea-level rise) and was primarily a strategy report, focusing on guidelines for studies, e.g., urging that studies of change in tropical cyclones and storm surges are of highest priority (IPCC, 1992).

For the IPCC Second Assessment Report (SAR, 1996) WGII reviewed climate change impacts and vulnerability plus mitigation options for greenhouse gases (GHG). In addition to two introductory primers, there were eighteen chapters on impacts and adaptation sorted primarily by land use (e.g., forests, rangelands, deserts, human settlements, agriculture, fisheries, financial services, human health) and seven chapters on mitigation sorted by sector (energy, industry, forests, other). The SAR made use of the new IPCC IS92 scenarios. Projections of 2100 sea level rise (15-95 cm) and temperature increase (1.0-3.5°C) were similar to the FAR's doubled-CO_2 scenario. The SAR notes "Impacts are difficult to quantify, and existing studies are limited in scope; Detection [of climate-induced changes] will be difficult," but some specifics are given (e.g., the number of people at risk of flooding from storm surges from sea level rise; the increase in malaria incidence). Vegetation models are used to map out projected changes in major biomes (see SAR WGII SPM Fig. 2) – the first such predictive figure in a WGII SPM. On mitigation, the SAR analyzed historical GHG emissions by sector and discussed technological options, but cost analysis was left to WGIII.

The Third Assessment Report of WGII (TAR, 2001) returned to impacts, adaptation, and vulnerability, returning mitigation to WGIII. It included five core chapters on sectors (water resources, ecosystems, coastal and marine, human settlements and energy, and financial services), eight regional chapters, plus two focus chapters on (i) adaptation, sustainable development, and equity, and (ii) vulnerability and reasons for concern. The TAR made the

first strong conclusion on attributing impacts: "recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems." Recent increases in floods and droughts, while affecting some human systems, could not be tied to GHG-driven climate change. The TAR introduced the "burning embers" diagram (TAR Fig. 2, updated in Chapter 18 of this report) as a way to represent "reasons for concern." The adaptive capacity, vulnerability and key concerns for each region were laid out in detail (TAR, 2001, Table 2).

The Fourth Assessment Report of WGII (AR4, 2007) retained the basic structure of the TAR with core chapters on sectors and regions. With the large increase in regional studies, AR4 concluded: "it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems." Many, more specific examples of attributed and projected impacts are reported with confidence levels, but many still remain qualitative. Two major graphics in the AR4 SPM (Figure 1-2 and Table 1-1) give many examples of projected impacts of climate change, but the state of the science – both of WGI climate projections and WGII impacts – remained too uncertain at the time to give more quantitative estimates of the impacts or necessary adaptation.

This Fifth Assessment Report of WGII (AR5) continues and expands the sector and regional parts. The AR5 considers a wide and complex range of multiple stresses that threaten the sustainability of human and ecological systems. Figure 1-3 gives examples of the wide range of stressors directly coupled to climate change (e.g., population, land-use change, projected temperature, heat waves, water availability), demonstrating the geographic heterogeneity. The focus on climate change and related stressors, and the resulting vulnerability, occurs throughout this report, including the expanded “reasons for concern” (Chapters 2 and 19, see also Section 1.1.4).

[INSERT FIGURE 1-3 HERE
Figure 1-3: Examples of the diversity and global heterogeneity of the many stressors related to climate change impacts, adaptation, and vulnerability: (a) Population, (b) Land-use and land-cover change, (c) Industrial CO_2 emissions, (d) Surface temperature change, (e) Heat waves, (f) Water availability, and (g) Vulnerability to climate change. Sources: (a) Global population density for year 2000 from the LandScan project at Oak Ridge National Laboratory and CIESIN, Columbia U. (http://sedac.ciesin.columbia.edu/data/collection/gpw-v3/maps); (b) Croplands and pasture/rangeland coverage from Foley *et al*. (2005); (c) Industrial sector energy/electricity-related CO_2 emissions ($GtCO_2$) for 1971-2000 (historical) and 2001-2030 (SRES B2) (AR4 WGIII TS.18 and Table 7.1, 7.2). EECCA = Countries of Eastern Europe, the Caucasus and Central Asia; (d) Surface temperature change projected for Dec-Jan-Feb, years 2046-2065 minus 1986-2005 under RCP8.5 from CMIP5 median (AR5 WGI Annex I); (e) Heat extremes based on Warm Spell Duration Index increase from 1980-1999 to 2081-2100 under SRES A2 normalized by standard deviation (SD) (SREX; after Fig.5 of Orlowsky and Seneviratne, 2011); (f) Water availability based on projected change of annual runoff (%) from 1981-2000 to 2081-2100 for SRES A1B (AR4 WGII Fig. 3.8, based on CMIP3); (g) Vulnerability to climate change in year 2050 (SRES A2, climate sensitivity 5.5°C, adapted from AR4 WGII Fig TS.19, 20.6).]

1.1.2.2. Treatment of Uncertainties in IPCC Assessment Reports: a Brief History and Terms Used in AR5

An integral feature of IPCC reports is communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Treatment of uncertainties and corresponding use of calibrated uncertainty language in IPCC reports have evolved across IPCC assessment cycles (Swart et al., 2009; Mastrandrea and Mach, 2011). In Working Group II, the use of calibrated language began in the contribution to the Second Assessment Report, in which most chapters used qualitative levels of confidence in findings presented in their Executive Summaries (IPCC, 1996). Starting with the Third Assessment Report (TAR), formal guidance across the Working Groups has been developed in each assessment cycle (Moss and Schneider, 2000; IPCC, 2005; Mastrandrea et al., 2010). The TAR guidance paper (Moss and Schneider, 2000) stated that “guidelines such as these will never truly be completed,” and an iterative process of learning and improvement of guidance has ensued, informed by experience in each assessment cycle. Each subsequent guidance paper has presented related but distinct approaches for evaluating and communicating the degree of certainty in findings of the assessment process.

The AR5 Guidance Note (summarized in Box 1-1) continues to emphasize a theme from all three guidance documents to date: the importance of clearly linking each key finding and corresponding assignment of calibrated

uncertainty language to associated chapter text, as part of the traceable account of the author team's evaluation of evidence and agreement supporting that finding

_____ START BOX 1-1 HERE _____

Box 1-1. Communication of Uncertainty in the Working Group II Fifth Assessment

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties (Mastrandrea et al., 2010), the Working Group II contribution to the Fifth Assessment Report relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment).

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The type and amount of evidence available varies for different topics, and that evidence can vary in quality. The consistency of different lines of evidence can also vary. Beyond consistency of evidence, the degree of agreement indicates the consensus within the scientific community on a topic and the degree to which established, competing, or speculative scientific explanations exist. Consistent evidence does not necessarily imply a high degree of agreement, if, for example, evidence is consistent but judged to be low in quality.

The Guidance Note provides summary terms to describe the available evidence: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, author teams additionally evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Figure 1-4 illustrates the relationship between the summary terms for evidence and agreement and the confidence metric. There is flexibility in this relationship; increasing confidence is associated with increasing evidence and agreement, but different levels of confidence can be assigned for a given evidence and agreement statement.

[INSERT FIGURE 1-4 HERE
Figure 1-4: Evidence and agreement statements and their relationship to confidence. The shading increasing towards the top-right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.]

In some cases, available evidence incorporates quantitative analyses, based on which uncertainties can be expressed probabilistically. In such cases, a finding can include calibrated likelihood language or a more precise presentation of probability. The likelihood terms and their corresponding probability ranges are presented below. Use of likelihood is not an alternative to use of confidence: an author team will have a level of confidence about the validity of a probabilistic finding. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence. When authors evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, the terms and associated meanings are:

Term*	**Likelihood of the outcome**
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms that were used in limited circumstances in the Fourth Assessment Report (*extremely likely:* 95–100% probability, *more likely than not:* >50–100% probability, and *extremely unlikely:* 0–5% probability) are also be used if appropriate.

_____ END BOX 1-1 HERE _____

1.1.3. Scenarios used as Inputs to Working Group II Assessments

A scenario is a story or image that describes a potential future, developed to inform decision-making under uncertainty (Parson et al. 2007). Historical uses of storylines for planning and analysis can be traced back to the first formalized war games that were developed for military officer training in 19th century Prussia (Brewer and Shubik, 1979). Scenarios are commonly used in the analysis of global climate change policy and assessment and have been part IPCC future climate projections since the FAR (1990), where WGIII generated four scenarios (Bau = business-as-usual, B, C, and D) that were used by WGI to project climate change. In the IPCC Supplementary Report (IPCC, 1992), a joint WGI-WGIII effort defined six new scenarios (IS92a-f) that were used in the SAR (1996). For the TAR (2001), the IPCC Special Report on Emissions Scenarios (SRES: Nakicenkovic et al., 2000) created many scenarios from four Integrated Assessment Models (IAMs), out of which a representative range of marker scenarios were selected (A1B, A1T, A1FI, A2, B1, B2). In the SRES, IPCC explicitly forbade climate-mitigation options. The SRES scenarios carried over into the AR4 (2007) and formed the basis for the large number of ensemble climate simulations (CMIP3), both historical and 21st century, which are in use for climate-change studies relevant to AR5 WGII.[1]

INSERT FOOTNOTE 1 HERE: The Coupled Model Intercomparison Project is an activity of the World Climate Research Programme's Working Group on Coupled Modelling. Climate model output from simulations of the past, present and future climate archived mainly in 2005-2006 constituted phase 3 of the Coupled Model Intercomparison Project (CMIP3). Similar climate simulations by an expanded set of models in 2011-2013 is being used in AR5 and constitutes phase 5 of the project (CMIP5). CMIP3 used the SRES scenarios, and CMIP5 used the RCP scenarios.]

With the AR5, the scenarios fundamentally changed: an ad hoc community of experts, anticipating AR5, built a new structure for scenarios called Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011) that defined the scenario from socio-economic path to emissions to greenhouse gas abundances and to global mean climate change using updated IAMs. These are primarily stabilization scenarios and labeled by their radiative forcing at the end of the century in W m^{-2} (RCP2.6, RCP4.5, RCP6.0, RCP8.5). The RCPs provide a flexible, interactive, and iterative approach to climate change scenarios without the governmental approval process. The connection between the anthropogenic emissions and climate forcing is weaker with the RCPs, which rely on a single parametric model (Meinshausen et al., 2011) than in previous assessments, which let the lead authors of the assessment report develop a best estimate. This aspect is assessed in AR5 WGI. The RCPs were used to drive multi-model ensembles of simulated climate change, historical and projected, designated CMIP5.

1.1.3.1. Comparison of RCP and SRES Scenarios

The WGI AR5 deals primarily with results from the RCP CMIP5, but this WGII assessment also uses results from the SRES CMIP3, and thus we identify similar or parallel scenarios from each set. The radiative forcing (RF in W m^{-2}) from the SRES and RCP scenarios are compared in Figure 1-5a. SRES A2 has a similar trajectory to RCP8.5, while SRES B1 matches RCP4.5. RCP6.0 has no simple analog: up to 2060, it is similar to both RCP4.5 and SRES B1; but after 2070, it lies between SRES B1 and B2. The RCP2.6 scenario, a strong mitigation scenario with net CO_2 uptake by 2100, falls well outside the SRES range, falling 2 W m^{-2} below SRES B2.

Total RF does not adequately describe the differences in climate change between SRES and RCPs. The RCPs universally adopt stringent mitigation policies for local air pollution and thus have much lower aerosol abundances than the SRES scenarios, which for the most part incorrectly ignored air quality regulations (AR5 WGI Tables AII.2.16-22). In terms of ozone and particulate matter precursor emissions, there is almost no overlap between

SRES and RCPs. In terms of surface ozone at the continental scale, after 2060 the RCPs are similar to low-end SRES B1 (AR5 WGI Tables AII.7.1-2).

Global mean surface temperature change for the scenarios (Figure 1-5b) shows bounding cases but no simple analogs. The AR5 RCP data is taken directly from the CMIP5 runs, whereas the AR4 data is based on a simple model, parameterized to match the different CMIP3 models (see figure caption). In terms of temperature change, RCP8.5 lies slightly above SRES A2, but below SRES A1FI. RCP4.5 follows SRES B2 up to 2060, but then drops to track SRES B1; whereas RCP6.0 has lower temperature change to start, following SRES B1 but then increasing towards SRES B2 by 2100. In general, scenarios SRES A1B, A1T and even B2 lie in the large gap between RCP8.5 and RCP4.5/6.0. The RCP2.6 temperature change stabilizes at about 1°C above the reference period (1986-2005), while for the 2090s, all SRES and the other RCPs span the range 1.8 – 4.1 °C.

[INSERT FIGURE 1-5 HERE
Figure 1-5: (a) Projected RF (W m^{-2}) and (b) global mean surface temperature change (°C) over the 21st century from the SRES and RCP scenarios. RF for the RCPs are taken from their published CO_2-eq (Meinshausen et al., 2011), and RF for SRES are from the TAR Appendix II (Table II.3.11). Comparable models are used in both RF calculations. The SRES RF are shifted upward by 0.12 W m^{-2} to match at year 2000. Temperature changes are decadal means based on the model ensemble mean CMIP5 data for the RCPs (see AR5 WGI Chapters 11, 12, Annex II tables). The same analysis applied to CMIP3 SRES A1B is also shown (yellow circles). The SRES temperatures (colored squares, AR4 WGI Figure 10.26) are based on a simple climate model tuned to the CMIP3 models. Thus the yellow circles and yellow squares differ by a few tenths °C.]

1.1.3.2. Shared Socio-economic Pathways

Complementing the development of the RCPs that represent radiative forcing, efforts are also currently underway to provide a linkage between them and a range of human development pathways. For that purpose, Shared Socioeconomic Pathways (SSPs) are being generated (Arnell et al., 2011) considering socioeconomic challenges to mitigation and socioeconomic challenges to adaptation. The SSPs include storylines, which are descriptions of the state of the world, Integrated Assessment Models (IAM) quantitative variables (such as population, GDP, technology availability), and other variables, not included in the IAMs, such as ecosystem productivity and sensitivity or the governance index. It is expected that they would facilitate comparison across research results of the Climate Models, the IAMs, and Impacts, Adaptation and Vulnerability (IAV) communities, and facilitate use of new climate modeling results in conjunction with IAV research. Several chapters of this report refer to the SSPs in their discussion of analysis of future impacts and vulnerability; Chapter 21 (21.3.3.1.3) addresses how the time lags in producing the RCPs and SSPs have limited the use of these scenarios in AR5.

1.1.4. Evolution of Understanding the Interaction between Climate Change Impacts, Adaptation, and Vulnerability with Human and Sustainable Development

The lack of progress in reducing greenhouse gas emissions at a global scale has fostered concern about unavoidable climate change impacts and has contributed to an increasing emphasis on vulnerability, adaptation, and development pathways. The possible range of socio-economic trajectories in developed and developing countries is among the largest sources of uncertainty in scenario building and climate predictions (Hawkins and Sutton, 2009). A deeper understanding of patterns of global development and the possibilities for the transformation of all countries towards sustainability is therefore a fundamental aspect of addressing climate change and its impacts.

The IPCC's first three Assessment Reports focused primarily on characterizing the biophysical impacts of climate change, with a progressively more elaborated understanding of the economic and social impacts. The last decade has seen major advances in the conceptual integration of the physical and social impacts of climate change. The Fourth Assessment Report asserted that "climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations" (IPCC 2007a, page 64). It offered a catalogue of

multiple stresses jointly impacting people and communities, and also highlighted questions of justice and equity in shaping development pathways in the context of climate change (IPCC 2007a, pages 811-841).

Vulnerability was defined in the TAR as a "function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, TAR, 2001b, page 388). Since then, the concept of vulnerability has acquired increased complexity as a multi-dimensional concept, also referring to structural conditions of poverty and inequality. This Report reveals substantive risks for socio-ecological systems in all regions, particularly in low-income economies. Literature reviewed in many chapters suggests that climate impacts could reverse past development achievements and hinder global efforts on poverty reduction, lead to human insecurity, displacement and conflict, maladaptation and negative synergies (for example, Barnett and O'Neill, 2010; Boyd and Juhola, 2009; Jerneck and Olsson, 2008; Klein et al., 2007; Ogallo, 2010; see also 13.2.1.; 12.2.1; 12.4.1; 12.5.1).

The importance of the social context in determining both resilience and vulnerability is encompassed by the notions of sensitivity and adaptive capacity and can be tracked using human development indicators. For example, adaptive capacity in many urban centers of the African continent is constrained by widespread poverty, lack of access to employment, inappropriate housing, or lack of access to water, sanitation and drainage, health care and education (8.2.4; 11.6.2, 22.4.4). Adaptation options and limits to high end warming in all countries are often contextualized in relation to socio-economic vulnerabilities and other stressors (Brown, 2012; New, Liverman, Schroeder and Anderson, 2010; Stafford Smith et al., 2011; World Bank, 2012; see 16.4.2.4). But concerted action to mitigate and address climate change along with increased adaptation practice creates an opportunity space for transformed pathways leading to increased resilience, low risk and low vulnerabilities. Sustainability, assuring and protecting the endurance of natural systems and equitable distribution in human systems, in the present and for the future, is thus a dynamic process and the context for climate resilience (see 20.2 and 20.3.3). The pathways identified in this report point to two eras. The era of climate responsibility, addressing the interconnectedness of multiple vulnerabilities for unavoidable impacts; and the era of climate options, the opportunity space to transform our actions toward a low risk and high resilient future.

A survey of the literature published since the last IPCC Report shows several key areas of emerging theoretical and methodological scholarship. Attention is being focused on devising and refining research methodologies to address the complexity of juxtaposing biophysical and social factors. This requires new approaches to transdisciplinarity, and the co-production of knowledge among stakeholders to enhance synergies between academic merit, policy relevance, and salience for users at the community level (Hegger et al., 2012; Pohl, 2011). A substantial amount of literature has emerged linking perspectives and methods, in particular resilience thinking, adaptive learning, anticipatory adaptation, sustainability science, welfare and social science research, vulnerability assessments, risk assessment and studies addressing the crucial role of mitigation in relation to development achievements (see for example, Beddoe et al., 2009; Cannon and Müller-Mahn, 2010; Folke et al., 2010; Reid et al., 2010). All point to the co-production of knowledge as a way to increase the saliency, legitimacy and credibility of the research process.

There is increased attention to questions of ethics, justice and responsibilities (for example, Arnold, 2011; Caney, 2012; Gardiner, 2011; Marino and Ribot, 2012; O'Brien et al., 2010; Pelling, 2010; Timmons and Parks, 2007). As basic needs such as energy, land, food or water become threatened, inequalities and unfairness may deepen leading to maladaptation and new forms of vulnerability. Responses to climate change may have unfair outcomes. For example, there are increasing cases of land-grabbing, large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities (Borras, McMichael, and Scoones, 2011, see also 14.7). Ethical perspectives are also important in relation to adaptation constraints and limits (see 16.7) and mitigation (see 1.3.4 and the Working Group III contribution to AR5). Addressing climate change vulnerabilities has become closely linked to addressing other injustices and reclaiming the role of democratic processes of social contestation against a perceived unfair distribution of wealth and resources and attention to underlying values, cultures and belief systems (Bond, 2011; Martinez-Alier et al., 2011; Shiva, 2005).

The relations with development are complex and contested. There is disagreement about some fundamental issues, in particular whether ideas of modernization, quality of life and increasing living standards based on consumption

patterns of western countries and exported to the global south through development aid are part of the problem (Brooks, Grist, and Brown, 2009; Grist, 2008; Schipper, 2007). The literature points to how inequalities, trade imbalances, intellectual property rights, gender injustice, or agricultural systems, for example, cannot be corrected with "development as usual", even if climate concerns are mainstreamed (Alston, 2011; Büscher et al., 2012; McMichael, 2009; OECD, 2009; Pogge, 2008; UNDP, 2007, 2011).

Practitioners link adaptation planning and policy instruments with ongoing development efforts. Climate change impacts are increasingly becoming a central issue in the work of United Nations development cooperation and specialized agencies, bilateral donor institutions, and international development Non Governmental Organizations (NGOs). At the same time, environmental institutions are increasingly paying attention to socio-economic contexts, institutions, culture and behaviors as key drivers for addressing environmental crises. The concept of "green" growth, for example, framed the 2012 Rio + 20 Earth Summit and has led to an academic debate on the opportunities and limits of this concept. However, concern about the incompatibility of growth with environmental goals remains (see 20.4.3), and proposals for alternative conceptions of growth (and growth reversal) have been proposed (Jackson, 2010).

The increase in adaptation literature and experience has led to the development of adaptation policy in many parts of the world, as reflected in all of the regional chapters of this report. The need for improved decision analysis has also led to a rapid increase in many approaches to climate change impact, adaptation and vulnerability assessments. At the policy level, individual country National Adaptation Programmes of Action and National Communication reports to the United Nations Framework Convention on Climate Change (UNFCCC) have focused primarily on physical climate change drivers and impacts. An analysis of National Communications documents submitted through 2004 by many of the developed countries (members of the Organisation for Economic Co-operation and Development) showed that climate change impacts and adaptation receive very limited attention relative to the discussion of greenhouse gas emissions and mitigation policies (Gagnon-Lebrun and Agrawala, 2006). The National Communications documents from 17 Latin American and Caribbean countries National Communications submitted through 2010 showed a similar pattern, with roughly 3% of the space (in pages) in these documents explicitly focused on adaptation (Figure 1-6). Progress towards adaptation is evident in some recent National Communications, however, such as the most recent National Communications from India and Iran, which devoted 28.8% (58 pages in a volume of 203) and 27.4% (52 pages in a volume of 190) respectively, to the topic of adaptation in their most recent National Communication.

[INSERT FIGURE 1-6 HERE
Figure 1-6: Distribution of topics related to impacts and vulnerability, adaptation, mitigation and greenhouse gas inventories (GHG inventories) in the First (1), Second (2) or Third (3) National Communications (NC) of several Latin American and Caribbean countries (Argentina, Belize, Bolivia, Brazil, Chile, Costa Rica, Cuba, Dominica, Ecuador, El Salvador, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Uruguay and Venezuela). Documents source: http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.phpUNFCCC.]

Some market theorists have sought to identify an appropriate and synergistic continuum between development and adaptation strategies and financing (Heltberg, Siegel and Jorgensen, 2009; Mearns and Norton, 2010; Richardson et al., 2011; OECD, 2009; USAID, 2008; World Bank, 2010). "Greener" versions of economic growth-driven development and revisited ideas of sustainable development have been proposed. Key instruments in this area are market-based mechanisms aiming to achieve synergies between mitigation and adaptation efforts, development financing and planning, the development of appropriate measurement and monitoring tools and links to energy needs, such as the "Clean Development Mechanism". But discussions are underway about the preconditions for market mechanisms, such as offsets, to work as intended (Liverman, 2010), the problems of carbon leakage, and the potential negative effects of mitigation strategies. An in-depth discussion of these interactions is given in Chapter 13, and Chapters 8, 11 and 12 identify central topics with particular relevance for poor communities. All regional chapters also assess this literature.

A concept emerging in the past years to avoid dichotomies between adaptation and mitigation is the term transformation. Within adaptation, we can distinguish between incremental and transformative adaptation, the later referring to changes in the fundamental attributes of a system in response to actual or expected climate and its

effects (Park et al., 2012). The IPCC Special Report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012) put forward a conception of transformation as a change in the fundamental attributes of a system, including technological, financial, regulatory, legislative and administrative (see 1.1.3; 20.5.4).

Emergent literature points to transformation of values, norms, belief systems, culture, and conceptions of progress and wellbeing in facilitating or preventing transformation (Kates et al., 2012; O'Brien, 2011; Pelling, 2011). Societal innovation and conditions for transformation of this nature requires a particular understanding of risk assessment, adaptive management, learning, innovation, and leadership and may lead to resilient development pathways (see also section 1.2.3 and Chapter 20). We see a focus on global transformation in the recent strategic reframing of global environmental change research (Rockström et al., 2009). But there are large gaps especially drawing from mainstream social and human sciences (Hackmann and St. Clair, 2012).

Climate science is advancing rapidly, with a wide range of new knowledge concerning diverse aspects of impacts, adaptation, and vulnerability, along with the knowledge assessed in other working groups of the IPCC. This provides an "opportunity space" for policy relevant information to support policy decisions leading to high resilience, low risk and low vulnerability and climate change is just one of many stressors that influence resilience. A conceptual approach that summarizes central issues presented in this Report emerges from describing existing planetary boundaries created by the interactions of biophysical and societal stressors within the context of a changing climate has been developed by Rockström et al. (2009) and Raworth (2012). This approach focuses on multi-sector risks today and in the future, with the concept of sustainability as a dynamic process that guarantees the resilience and persistence of natural and human systems. In this conceptual framework of existing stressors and the boundaries they create, actions to reduce climate change impacts can be envisioned as a double edged sword: entailing both an era of responsibility and an era of climate options. On the one hand there is an option for responsible action to protect those vulnerable to unavoidable impacts. This era of responsibility requires increasing the resilience space by reducing both societal and biophysical stressors and, thus, an increased emphasis on adaptation. On the other hand, there is an opportunity space, the era of climate options, which through mitigation can reduce the rate of planetary warming and its impacts. The decisions and pathways that societies choose in the opportunity space, informed by science, observation and experience, will affect the degree of resilience in human and natural systems of the future (Figure 1-7).

[INSERT FIGURE 1-7 HERE
Figure 1-7: Conceptual framework for assessing interactions between biophysical and societal stressors that impact the resilience of natural and human systems today and in the future. Actions, including climate change adaptation and mitigation, taken in the opportunity space lead to a diverse range of pathways and outcomes – toward a future of high risk, high vulnerability and low resilience space or toward a future of low risk, low vulnerability and high resilience space.]

1.2. Major Conclusions of the WGII Fourth Assessment Report

1.2.1. Observed Impacts

Evidence presented in Chapter 1 of the WGII Fourth Assessment Report (AR4) (Rosenzweig *et al*., 2007, page 81) indicated that "Physical and biological systems on all continents and in most oceans are already being affected by recent climate changes, particularly regional temperature increases (*very high confidence*)". In terrestrial ecosystems, warming trends were consistent with observed change in the timing of spring events and poleward and upward shifts in plant and animal ranges. Other examples of observed change presented in Chapter 1 of AR4 included changes in the phenology of 542 plant species in Europe and 145 species of wild animals and plants in the Northern Hemisphere. The authors of Chapter 1 also concluded that the geographical locations of observed changes during the period 1970-2004 are consistent with spatial patterns of atmospheric warming. The types of hydrologic changes reported ranged from effects on snow, ice and frozen ground; the number and size of glacial lakes; increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers; effects on thermal structure and water quality of rivers and lakes; and changes associated with more intense drought and heavy rains in some

regions. The authors of AR4 concluded from a synthesis of studies "**that the spatial agreement between regions of significant warming and the locations of significant observed changes is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems**" (IPCC, 2007d, page 9).

Observed regional impacts to human systems were less obviously attributed to anthropogenic climate change. The authors of AR4 concluded that "**There is *medium confidence* that other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers"** (IPCC, 2007c, page 3)**.** They presented evidence on the effects of temperature increases on agricultural and forestry management at Northern Hemisphere higher latitudes (e.g. earlier spring planting of crops, alterations in disturbance regimes of forests due to fires and pests); on some aspects of human health (e.g. heat-related mortality in Europe, changes in infectious disease vectors in some areas, and allergenic pollen in Northern Hemisphere high and mid-latitudes); and some human activities in the Arctic (e.g. hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports)".

The authors of AR4 concluded that "**Recent climate changes and climate variations are beginning to have effects on many other natural and human systems, but the impacts have not yet become established trends**" (IPCC, 2007d, page 9). In mountain regions melting glaciers enhanced risk of glacier lake outburst floods on settlements; in the Sahelian region of Africa warmer and drier conditions had detrimental effects on some crops; and in coastal areas sea-level rise and human development contributed to losses of coastal wetlands and mangroves and to increases in damage from coastal flooding (Chapter 1 of WGII-AR4).

1.2.2. Advances in the Assessment Process

The authors of the Working Group II contribution to AR4 noted that the demand for assessments had grown significantly since the release of the IPCC Third Assessment Report (TAR), thereby motivating researchers to expand the ranges of approaches and methods in use and to develop characterizations of future conditions (scenarios and related products) required by those methods. In particular, they indicated that major advancements in CCCIAV assessment were related to the need for improved decision analysis, the inputs from stakeholders, the role of non-climate factors, the increase in spatial and temporal resolution of scenario information, the characterization of the future including mitigation scenarios, large-scale singularities and probabilistic futures (Chapter 2 WGII-AR4, page 135).

1.2.3. Key Vulnerabilities and Reasons for Concern

In an effort to provide some insights into the seriousness of the impacts of climate change, the authors of the IPCC Third Assessment Report (IPCC, 2001b) identified five ''Reasons for Concern'' (RfC's). Considering new evidence of observed changes on every continent, coupled with a more thorough understanding of the concept of vulnerability, the authors of AR4 concluded that: "The five 'reasons for concern' identified in the TAR remained a viable framework to consider key vulnerabilities. These 'reasons' are assessed here to be stronger than in the TAR. Many risks are identified with higher confidence. Some risks are projected to be larger or to occur at lower increases in temperature. Understanding about the relationship between impacts (the basis for 'reasons for concern' in the TAR) and vulnerability (that includes the ability to adapt to impacts) has improved. This is due to more precise identification of the circumstances that make systems, sectors and regions especially vulnerable and growing evidence of the risks of very large impacts on multiple-century time scales" (IPCC 2007c, page 19).

Plenary-approved language in the SPM of Synthesis Report of the AR4 (page 19) summarized the RfCs as follows:

- *Risk to Unique and Threatened Systems*: There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase.
- *Risks of Extreme Weather Events*: Responses to some recent extreme events reveal higher levels of vulnerability than the TAR. There is now higher confidence in the projected increases in droughts, heat waves and floods, as well as their adverse impacts.

- *Distribution of Impacts*: There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. There is increasing evidence of greater vulnerability of specific groups such as the poor and elderly not only in developing but also in developed countries. Moreover, there is increased evidence that low-latitude and less developed areas generally face greater risk, for example, in dry areas and megadeltas.
- *Aggregate Impacts*: Compared to the TAR, initial net market-based benefits from climate change are projected to peak at a lower magnitude of warming, while damages would be higher for larger magnitudes of warming. The net costs of impacts of increased warming are projected to increase over time.
- *Risks of Large Scale Discontinuities*: There is high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales.

Perhaps more importantly for the AR5, careful reading of the AR4 reveals that authors also added some increased texture to each RfC by moving from impacts to vulnerabilities and their expanding scope – health metrics were added to the "Aggregate Impacts" RfC, for example; and widespread extinctions of species were added to the "Risks of Large Scale Discontinuities" (which had been called "Singularities" in the TAR). This is evidence that the RfC's evolve over time as knowledge and nuance expands with new knowledge.

Chapter 18 of this report uses RfC's to organize much of its synthesis of detection and attribution confidence conclusions across the volume; the point there is to expand our understanding of how observed and attributed impacts and vulnerabilities support the significance of each of the five reasons. Chapter 19 of this report will return to the RfC's as a unifying construction, expanding the scope to reflect risks and vulnerabilities – a continuation of the evolutionary process of their applicability.

The authors throughout the AR4 concluded that the evidence of vulnerability to observed climate change is most prevalent in places where warming has been the greatest and in systems that are more sensitive to temperature. Marine, freshwater and terrestrial biological systems are particular sensitive to observed temperature warming (e.g. changes in morphology, physiology, phenology, reproduction, species distribution, community structure, ecosystem processes and species evolutionary processes, etc.). Agricultural ecosystems have shown changes in phenology, management practices and yields. Human diseases linked with temperature sensitive vectors have shown spreader distribution. Natural systems are generally considered more affected than managed systems. Physical and biological systems appear to be more vulnerability to extreme events or exceptional episodes than to mean climate change (e.g. agricultural response and mortality occurring in the 2003 heat waves in Europe). Some regions, such as heavily populated deltas and low-lying islands, were identified as hotspots of societal vulnerability.

1.2.4. Risk Assessment as a Response to Climate Change

A fundamental point of departure to be drawn from the AR4 for the entire AR5 is that: "**Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk"** (IPCC, 2007c). This plenary approved language from the AR4 Synthesis Report SPM elevates the concept of risk in the assessment process. As indicated in the elaboration of this conclusion recorded in Topic 5 of IPCC AR4: "Risk management techniques can explicitly accommodate sectoral, regional and temporal diversity, but their application requires information about not only impacts resulting from the most likely climate scenarios, but also impacts arising from lower-probability but higher-consequence events and the consequences of proposed policies and measures. Risk is generally understood to be the product of the likelihood of an event and its consequences. Climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations (IPCC 2007c, page 64)".

IPCC (2007a) offered several summary glimpses at the risks from climate change and changes in climate variability that could be expected as global mean temperatures rise in Chapter 20 and its own SPM. These risks were calibrated by the various author teams in the most appropriate metric (i.e., not converted universally to economic indicators) and various levels of warming that could be experienced over the coming century. While they were also cast against ranges of warming at the end of the century for various manifestations of the SRES storylines, most of the indicated risks were drawn from the A2 alternative scenario for which specific trajectories of driving variables (like population), associated rates of change (in climate and socio-economic development), and corresponding levels of adaptive capacity were implied. They offered an alternative portrait for regional impacts so that the distributional implications of climate change might be inferred.

Transferring these insights into other scenarios from the SRES suite and/or the new RCP scenarios must be done with care, and is a task that has been picked up by the authors of the AR5. As the AR5 takes a risk-based perspective in response to governments' recognition that decision makers must adopt an "iterative risk-management approach", authors will have to add conclusions to which lower confidence has been assigned if they relate to "key vulnerabilities" with large consequences. The criteria identified in Chapter 19 of IPCC AR4 (2007b) can be applied in sorting through the literature of sectoral and regional impacts.

1.2.5. Interaction of Adaptation and Mitigation in a Policy Portfolio

The climate community in general and decision-makers in particular have begun to understand that coping with risks of climate change will involve a portfolio of initiatives that will evolve iteratively over time as new information about the workings of the climate system and new insights into how various responses are actually working and penetrating the global socio-economic structure. The suite of assessments offered under the rubric of "America's Climate Choices" by the U.S. National Academy of Sciences as well as the report of the New York (City) Panel on Climate Change provide ample evidence to these points. The authors of the IPCC AR4 made these points and thereby offered guidance to the AR5 process when it reported that: "**There is high confidence that neither adaptation nor mitigation alone can avoid all climate change impacts; however, they can complement each other and together can significantly reduce the risks of climate change.** Adaptation is necessary in the short and longer term to address impacts resulting from the warming that would occur even for the lowest stabilization scenarios assessed. There are barriers, limits and costs, but these are not fully understood. Unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt. The time at which such limits could be reached will vary between sectors and regions. Early mitigation actions would avoid further locking in carbon intensive infrastructure and reduce climate change and associated adaptation needs" (IPCC 2007c, page 19).

IPCC (2007c, page 19) also conveyed a sense of urgency by concluding that "**Many impacts can be reduced, delayed or avoided by mitigation. Mitigation efforts and investments over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels. Delayed emission reductions significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts**."

WGII AR5 devotes considerable attention to this interface and the mechanisms for iterating as new information emerges in a collection of chapters designed explicitly for this purpose. Meanwhile, author teams for the sectoral and regional chapters will work to bring insights on adaptation to bear on the risk summaries that they will produce. In these efforts, we begin with the recognition from the Synthesis Report of IPCC Working Groups II, II and III (2007c, page 14) that: "**A wide array of adaptation options is available, but more extensive adaptation than is currently occurring is required to reduce vulnerability to climate change. There are barriers, limits and costs, which are not fully understood.** Societies have a long record of managing the impacts of weather- and climate-related events. Nevertheless, additional adaptation measures will be required to reduce the adverse impacts of projected climate change and variability, regardless of the scale of mitigation undertaken over the next two to three decades. Moreover, vulnerability to climate change can be exacerbated by other stresses. These arise from, for example, current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalization, conflict and incidence of diseases such as HIV/AIDS. Some planned adaptation to climate change is

already occurring on a limited basis. Adaptation can reduce vulnerability, especially when it is embedded within broader sectoral initiatives. There is *high confidence* that there are viable adaptation options that can be implemented in some sectors at low cost, and/or with high benefit-cost ratios. However, comprehensive estimates of global costs and benefits of adaptation are limited."

In addition, the AR4 authors concluded in IPCC (2007c, page 14) that **"Adaptive capacity is intimately connected to social and economic development but is unevenly distributed across and within societies.** A range of barriers limits both the implementation and effectiveness of adaptation measures. The capacity to adapt is dynamic and is influenced by a society's productive base, including natural and man-made capital assets, social networks and entitlements, human capital and institutions, governance, national income, health and technology. Even societies with high adaptive capacity remain vulnerable to climate change, variability and extremes." The challenge in extending this list and expanding understanding about adaptation and sustainable development at the time of the AR4 was attributed to the diversity of context, the paucity of actual adaptation to climate change that had been analyzed in the peer review literature, and the broader context within which multiple sources of stress are recognized.

1.2.6. Gaps in the Assessment of Impacts, Adaptation, and Vulnerability Identified in AR4

While the scope and complexity of climate change impact assessments have expanded with each IPCC synthesis report since 1990, several information gaps and shortcomings were identified in the Working Group II contribution to IPCC Fourth Assessment Report (AR4) (IPCC 2007a). Examples of some of the gaps cited in the Summary for Policymakers (SPM), the Technical Summary (TS) and individual chapters of AR4 are indentified below in categories that reflect apparent levels of progress that can be gauged by the contents of AR5.

Gaps and limitations for which significant progress is evident in the literature since AR4

- A lack in geographic balance in data and literature on observed changes [SPM, page 8]
- Difficulty discerning effect of regional climate changes due to adaptation and non-climatic drivers [SPM, page 9] and proximity to thresholds and tipping points [TS 6.1]
- Impacts under different assumptions about how the world will evolve in future – societies, governance, technology and economic development [TS 6.1]
- Lack of understanding regional sea level rise trends since 1950 and lack of information concerning the persistence of regional trends through the 21st century; lack of sea level rise scenarios for beyond 2100 [Ch. 6 and TS 6.2]
- Most AR4 studies of future climate change were based on a small number of studies using SRES scenarios, especially the A2 and B2 families. This allowed some limited, but incomplete, characterisation of the potential range of futures and their impacts [TS 6.2 and Ch. 2.3]
- Inadequacies of climate models to simulate changes in patterns of extreme events, particularly with respect to precipitation changes, at a scale that is useful for assessing future climate-related impacts on water resources [TS 6.2, Ch 5.8.2].
- Understanding of the likely future impacts of climate change was hampered by lack of knowledge regarding the nature of future changes, particularly at the regional scale and particularly with respect to precipitation changes and their hydrological consequences on water resources, and changes in extreme events, due in part to the inadequacies of existing climate models at the required spatial scales [TS 6.2 and Ch. 2.5, 3.3.1, 3.4.1, 4.3].
- Only a small amount of literature on the costs of climate change impacts could be found for the WGII Fourth Assessment Report [TS and Ch. 5.6, 6.5.3, 7.5]. Debate still surrounded the topic of how to measure impacts, and which metrics should be used to ensure comparability [TS and Ch. 2.2.3, 19.3.2.3, 20.9].
- Impact of climate change on utilization of biofuels and how the use of biofuels affects competition for land [Ch. 5.8.2]; high uncertainty about vulnerabilities and adaptation potentials in human systems [Ch. 7.8]; and the availability of few national health impact assessments [Ch. 8.8]
- Literature on adaptation costs and benefits was limited and fragmented [TS and Ch. 17.2.3]. It focused on sea-level rise and agriculture, with more limited assessments for energy demand, water resources and transport. There was an emphasis on the USA and other OECD countries, with a few assessments having

been conducted in developing countries [Ch. 17.2.3]. There was growing evidence, however, that adaptation measures are being implemented on a limited basis in developing and developed countries [TS 5.1].

- AR4 recognized that synergies exist between adaptive capacity and sustainable development, but further research was required to determine factors that contribute to this synergy [TS 6.2 and Ch. 20.9].

Gaps and limitations for which more modest or little progress is evident in the literature since AR4

- Inadequate understanding of the impacts of abrupt change events, such as collapse of the North Atlantic Meridional Overturning Circulation. However, without a better understanding of the likelihood that such events will be manifested at the regional scale, it will not be possible to carry out impact assessments of such events [TS and Ch. 6.8, 7.6, 8.8, 10.8.3].
- Wide range in future sea level rise estimates and high uncertainty about timing of sea level rise (lack of time slices for sea level rise due to uncertainties concerning ice sheet dynamics, only given end of century estimates)[Ch.10]
- Poor understanding of trends and future changes in wave regime – important particularly to small island nations [Ch. 6 and Ch. 16]
- Lack of high-quality observations that are essential for full understanding of causes and for unequivocal attribution of present-day trends to climate change [TS 4.8 and 6.2].

Understanding of abrupt climate change and the impacts of such events as the Progress towards resolving some of the shortcomings in data and reporting cited above were addressed in the IPCC Special Report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012) that was produced jointly by Working Groups I and II (see Section 1.3.1 in this chapter). The WGI contribution to AR5 has advanced our understanding of the drivers of ice sheet decline and contains new estimates of sea level rise that are updated with mass balance trends and models of ice sheet at time scales that are relevant to decision making. Though not reflected due to scale limitations in IPCC AR5 assessment, progress with high resolution downscaling of climate information has helped address the needs of natural resource managers operating at a sub-regional scale in many parts of the world.

1.3. Major Conclusions of More Recent IPCC Reports

Since the publication of the Fourth Assessment Report (AR4) in 2007 the IPCC has produced two Special Reports: the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), produced by Working Group III and published in 2011, and a Special Report on "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), published in 2012. In addition, the AR5 has staggered the assessment work for its three working groups. The Report of Working Group I was published in 2013 and the Report of Working Group III will be published later in 2014. In this section we summarize the major conclusions of the SREX, the SSREN and the Working Group I and III contributions to the AR5. We focus on the key findings and the fundamental framings and conceptual innovations these Assessment Reports bring to the development of the chapters that form the Working Group II contribution to AR5.

One aspect that cuts across the Working Groups is the detection of climate change or its impacts observed to date (2011 for WGI), the attribution of that climate change to the observed increases in greenhouse gases (a measure of the human forcing of climate change), the attribution of local climate impacts to the observed warming of that region, and the projection of these impacts and climate change into the 21st century. Table 1-1 gives a summary of phenomena for which such detection, attribution, or projection has been made across the Working Groups. A schematic presentation of this detection-attribution-projection sequence from preceding reports is given in Figure 1-8. For AR5 WGII attribution, see Chapter 18, and for projections, see the other chapters.

[INSERT TABLE 1-1 HERE
Table 1-1: Observed, attributed, and projected changes in the climate system, including impacts, adaptation, mitigation and vulnerability to climate change.]

[INSERT FIGURE 1-8 HERE
Figure 1-8: Climate change and its impacts detected to date (horizontal axis) is plotted against (left panel) attribution of those changes to greenhouse gases and (right panel) projection of those changes into the 21st century for a global warming exceeding 2°C. Only phenomena with a detection, attribution or projection at high confidence levels or with quantifiable uncertainty are shown. All phenomena are defined in Table 1-1 where the color coded symbols and likelihood are defined. Results are taken from the AR4, SREX, and AR5 WGI, but primarily from WGI because the attribution is to the observed increase in greenhouse gases that has driven anthropogenic climate change, rather than as in WGII to the regional/local observed warming. For AR5 WGII results, see inter alia Chapters 18 and 19.]

1.3.1. IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

The SREX (IPCC, 2012) is the first IPCC Special Report produced jointly by Working Groups I and II and is the first IPCC report to focus on risk management. The report integrates perspectives from historically distinct research communities studying climate science, climate impacts, climate adaptation and disaster risk management. The SREX assesses relationships between climate change and the characteristics of extreme weather and climate events. The report and its Summary for Policymakers provide information on existing societal exposure and vulnerability to climate-related extreme events and disasters; observed trends in weather- and climate-related disasters and disaster risk management; projected changes in weather and climate extremes and projected disaster losses during the 21st century; approaches for managing the increasing risks of climate extremes and disasters; and implications for sustainable development. One chapter of the SREX is devoted to fourteen case studies that illustrate the impacts of extreme climate events and options for risk management and adaptation, such as early-warning systems, new forms of insurance coverage, and expansion of social safety nets.

1.3.1.1. Themes and Findings of SREX

The most relevant results of the assessment carried out by the SREX author team can be synthesized along the three major themes: changing weather and climate-related extreme events, trends in disaster losses, and managing the risks of extreme events and disasters. Some of the findings presented in the SREX concerning the type, magnitude and frequency of extreme weather and climate events are presented in Table1-1. Examples of findings from the SREX report concerning trends in disaster-related losses and challenges in managing risks are presented below:

- Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability (*high confidence*, based on *high agreement, medium evidence*). [SPM, 4.5.1, 4.5.3, 4.5.4]. Trends in losses have been heavily influenced by increasing exposure of people and economic assets *(high confidence)*. [SPM, 4.5.3]
- Economic, including insured, disaster losses associated with weather, climate, and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of gross domestic product (GDP) are higher in developing countries (*high confidence*). [SPM, 4.5.2, 4.5.4]
- Deaths from natural disasters occur much more in developing countries (*high confidence)*. From 1970 to 2008 for example, more than 95% of deaths from natural disasters were in developing countries. [SPM, 4.5.2, 4.5.4]
- Development practice, policy and outcomes contribute to shaping disaster risks (*high confidence):* skewed development that may lead to environmental degradation, unplanned urbanization, failure of governance or reduction of livelihood options result in increased exposure and vulnerability to disasters. [SREX 1.1.2, 1.1.3 and 2.2.2, 2.5]
- Managing risks is an iterative process involving monitoring, research, evaluation, learning and innovation can reduce disaster risk in the context of climate extremes (*robust evidence, high agreement)* [SPM, 8.63, 8.7]
- Risk management works best when tailored to local circumstances. Combining local knowledge with additional scientific and technical expertise helps communities reduce their risk and adapt to climate change (*robust evidence, high agreement*). [SPM, 5.4.4].

- Actions ranging from incremental improvements in governance and technology to more transformational changes are essential for reducing risk from climate extremes (*robust evidence, high agreement)*. [SPM, 8.6, 8.6.3, 8.7]
- Effective risk management generally involves a portfolio of actions to reduce and transfer risks and to respond to events and disasters, rather than a singular focus on any one type of action (high confidence)., Successful strategies include both hardware measures and soft solutions such as from improving infrastructure to building individual and institutional capacity building., in order to reduce risk and respond to disasters (*high confidence*). [SPM, 1.1.2, 1.1.4, 1.3.3]
- Post-disaster recovery and reconstruction provide an opportunity for reducing the risks posed by future weather- and climate-related disasters (*robust evidence, high agreement*). [SPM, 5.2.3, 8.4.1, 8.5.2] However, short-term measures to protect people from immediate risks can increase future risks, such as improvements in levees encouraging further development in flood plains (*medium evidence, high agreement*).
- Socio economic, demographic, health related differences, access to livelihoods, good governance and entitlements are some of the factors that lead to inequalities between people and countries. Inequalities influence local coping and adaptive capacity and pose challenges for risk management systems from local to national levels (*high agreement, robust evidence*) [SREX 5.5.1, 6.2, 6.3.2, 6.6].
- Many measures for managing current and future risks have additional benefits, such as improving peoples' livelihoods, conserving biodiversity, and improving human well-being (*medium evidence, high agreement*). [SPM, 6.3.1, Table 6-1].
- Many measures, when implemented effectively, make sense under a range of future climates (*medium evidence, high agreement*). These "low regrets" measures include systems that warn people of impending disasters; changes in land use planning; sustainable land management; ecosystem management; improvements in health surveillance, water supplies, and drainage systems; development and enforcement of building codes; and better education and awareness. [SPM, 5.3,1, 5.3.43, 6.3.1, 6.5.1, 6.5.2, 7.4.3 and Case Studies 9.2.11, 9.2.14]
- Post-disaster recovery and reconstruction provide an opportunity for reducing the risks posed by future weather- and climate-related disasters (*robust evidence, high agreement*). [SPM, 5.2.3, 8.4.1, 8.5.2] However, short-term measures to protect people from immediate risks can increase future risks, such as improvements in levees encouraging further development in flood plains (*medium evidence, high agreement*).

1.3.1.2. Advances in Conceptualizing Climate Change Vulnerability, Adaptation, and Risk Management in the Context of Human Development

The conceptual framing of the SREX reflects the diversity of expert communities involved in this assessment. It links exposure and vulnerability with socio-economic development pathways as determinants of the impacts and the likelihood of disaster risk for both human society and natural ecosystems. It is important to note that the SREX acknowledges the fundamental role that values and aspirations play in people's perception of risk, change and causality, and on imagining present and future situations. This value-based approach is put to work as a tool for managing the risks of extreme events and disasters enabling the recognition that socio-economic systems are in constant flux, and that there are many conflicting and contradictory values at play. The conceptual framing of the problem space offered by the SREX (illustrated in figure 1-1 of the SREX SPM) serves as a point of departure for many chapters in this AR5. Equally important for the AR5 is the conceptualization of a feasible solution space offered in the SREX. As stated in the summary of key findings, there is robust evidence and high agreement that addressing the risks calls for "actions ranging from incremental improvements in governance and technology to more transformational changes are essential for reducing risk from climate extremes" (SREX Fact Sheet, IPCC, 2011b).

1.3.2. Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)

The SRREN (IPCC, 2011a) assesses existing literature on the relationship between renewable energy sources and the mitigation of climate change. It examines six renewable energy sources: bioenergy, direct solar energy, geothermal energy, hydropower, ocean and wind energy in terms of available technologies, technical potential and associated costs. It examines the challenges of integrating renewable energy sources into existing electrical power systems, heating and cooling networks, gas grids and liquid fuel systems and provides an in-depth assessment of the relationship of renewable energies to goals of sustainable development. In a review of 164 scenarios, the role of renewable energy sources in climate change mitigation is compared within a portfolio of mitigation options that include end-use energy efficiency, nuclear energy and fossil-fuel based energy with carbon capture and storage (CCS). Finally, for policy-makers interested in scaling up renewable energy for climate change mitigation goals, supporting policies for the development and deployment of these technologies are assessed.

Though renewable energy accounted for only 12.9% of the total primary energy supply in 2008, the SRREN shows that the deployment of renewable energy technologies has been increasing rapidly in recent years, often associated with cost reductions that are expected to continue with further technical advances. Biomass accounted for the majority of this total (10.2% out of 12.9%), much of which is traditional biomass in developing countries. Despite the small contribution of renewable energy to current energy supplies, in its assessment the SRREN shows the global technical potential of renewable energy to be substantially higher than the global energy demand. It is therefore not the technical potential of renewable energy that constrains its development, but rather economic factors, system integration and infrastructure constraints, public acceptance and sustainability concerns. The assessment of lifecycle assessment studies in the SRREN showed that GHG emissions associated with the generation of electricity from renewable energy technologies are, in general, significantly lower than those associated with fossil fuels, and under a range of conditions, also less than fossil fuels employing CCS. The percent increase of renewable energy in future primary energy supplies varies widely across scenarios, though a majority indicate a significant increase – from 64 EJ/yr total RE production in 2008 to more than 173 EJ/yr in 2050. Even under baseline scenarios the deployment of renewable energies is expected to increase, many showing to levels more than 100 EJ/yr. The growth of renewable energy is typically expected to be widespread across the world, though in the long-term (2050) most development is expected in non-Annex I countries (IPCC, 2011a).

Several SRREN findings have clear linkages with this assessment of climate change impacts, adaptation and vulnerability, as captured in Table 1-2.

[INSERT TABLE 1-2 HERE
Table 1-2: Links between SRREN and the Working Group II contribution to the Fifth Assessment Report.]

1.3.3. Relevant Findings from IPCC Working Group I Fifth Assessment Report First-Order Draft

[PROVISIONAL - This WGII SOD version is shortened, but not yet updated to reflect the WGI SOD/FGD.]

Key findings from the WGI FOD Executive Summaries relevant to WGII are summarized here. All summary statements below have *high confidence* attached to them in the WGI AR5 and are likely or higher if quantified uncertainty is given.

Climate Models. For AR5, a range of "climate" models are considered, including: coupled Atmosphere-Ocean General Circulation Models (AOGCMs) used in both climate reconstructions and future projections; their extension to 'Earth System' Models (ESMs) that include biogeochemical cycles; higher resolution, limited-area Regional Climate Models (RCMs) used to downscale global climate results; Earth System Models of Intermediate Complexity (EMICs) used primarily for exploring parameter uncertainty [WGI-9]. Datasets of multi-model ensembles for both past and future climate are available from Coupled Model Intercomparison Projects (CMIP3 and CMIP5[1]) and the Coordinated Regional Downscaling Experiment (CORDEX) [WGI-9]. The ability of climate models to simulate historical climate, its change, and its variability, has improved in many important respects since the AR4 [WGI-9]. RCMs are able to add value to coarser-resolution global model results, providing realistic spatial detail and improved representation of climate extremes [WGI-9]. Errors and biases in models tend to be related to

smaller-scale features [WGI-9]. Lack of agreement across models on local trends is often a result of natural variability, rather than models actually disagreeing on their forced response [WGI-12].

Climate change comparison with AR4. The new CMIP5 results are similar to the AR4 CMIP3 results for the near term [WGI-11] but differ in the long term (see 1.1.3.1 and WGI-12). Multi-model average patterns of change in temperature and precipitation from CMIP3 and CMIP5 ensembles, once normalized per 1ºC of global temperature change, present a high degree of pattern correlation, with values larger than 0.9 for temperature change patterns and larger than 0.8 for precipitation patterns [WGI-12]. The characteristic stability of robust geographical patterns of temperature change (less so for precipitation) during a transient experiment remains valid in the new generation of models participating in CMIP5 [WGI-12]. Agreement and thus confidence in projections is higher for temperature related quantities than for those related to the water cycle or circulation [WGI-12]. In cumulative terms, the 2°C temperature target implies cumulative carbon emissions of about 1000–1300 GtC, of which about 520 GtC were already emitted by 2011 [WGI-12].

Temperatures. The global combined land and ocean temperature data show a temperature increase of about 0.8°C for the period 1901–2010 and about 0.5 °C for 1979–2010 when estimated by a linear trend [WGI-2]. Over every continent except Antarctica, anthropogenic influence (GHG increases) has made a substantial contribution to surface temperature increases [WGI-10]. Across all RCP scenarios, the multi-model global mean warming over the period 2016–2035 relative to the reference period 1986–2005 lies in a narrow range about 0.7°C [WGI-11]. Globally and regionally, the surface temperature response is fairly independent of scenario until after 2040 [WGI-11]. For RCP4.5, 6.0 and 8.5, global temperatures exceed 2ºC warming (over pre-industrial) by 2100 [WGI-12]. Based on model results and other studies, RCP2.6 pathway may or may not achieve the policy-relevant objective of no more than 2°C global warming relative to pre-industrial [WGI-12].

Precipitation. Precipitation in the tropics has increased over the last decade reversing the drying trend that occurred from the mid-1970s to mid-1990s reported in the AR4 [WGI-2]. New evidence has emerged for the detection of anthropogenic influence on aspects of the water cycle: on zonal patterns of global precipitation changes, including reductions in low latitudes and increases in northern hemisphere mid to high latitudes [WGI-10]. There is limited, if any, evidence and no agreement that the small-scale impact of aerosols on cloud microphysical structure translates into a significant regional impact in terms of precipitation amount (beyond orographic locations) [WGI-7]. Precipitation in the near-term is projected to increase in regions of tropical precipitation maxima and at high latitudes, with general decreases in drier regions of the tropics and sub-tropics, but projections vary considerably from model to model [WGI-11]. For the near term, CMIP5 projections confirm a clear tendency for increases in heavy precipitation events in the global mean as in AR4, but there are significant variations across regions [WGI-11]. Global-scale precipitation is projected to gradually increase in the 21st century, approximately 2% K^{-1} [WGI-12]. Average precipitation in a much warmer world will not be uniform, with regions experiencing increases, or decreases or no much change at all, but many mid-latitude arid and semi-arid regions will likely experience less precipitation [WGI-12]. Largest precipitation changes over northern Eurasia and North America are projected to occur during the winter [WGI-12].

Hydrology, Flooding and Droughts. Extended intervals of drought associated with weak Indian Summer Monsoon in the last 2000 years may have been synchronous across a large region of southeastern Asia [WGI-5]. The most recent and most comprehensive analyses of river runoff do not support the AR4 conclusion that global runoff has increased during the 20th Century [WGI-2]. Projections of soil moisture and drought remain relatively uncertain [WGI-12]. Decreases in runoff are projected in southern Europe, the Middle East, and southwestern United States, but increases in high latitude runoff, as with AR4 [WGI-12]. A shift to more intense individual storms and fewer weak storms is projected, with possibly more frequent/intense periods of agricultural drought (from intervening dry spells between intense individual storms) [WGI-12].

Sea Level. Under all the RCP scenarios, the time-mean rate of global mean sea level rise during the 21st century is very likely to exceed the rate observed during 1971–2010 [WGI-13]. For the period 2081 to 2100 compared to 1986 to 2005, GMSL rise is projected to lie in the range 0.27–0.50 m for RCP2.6, 0.32–0.56 m for RCP4.5 and RCP6.0, and 0.41–0.71 m for RCP8.5 [WGI-13]. Under RCP 8.5, the likely range reaches 0.84 m in 2100, but larger values than these ranges cannot be excluded [WGI-13]. The contribution from rapid changes in ice-sheet dynamics – 0.12

m from the two ice sheets combined – is the main reason why these ranges are higher than those given in the AR4 [WGI-13]. Regional patterns of projected sea level change, while overall positive, deviate significantly from the global mean [WGI-13]. Extreme wave heights have likely increased over the past 60 years, in keeping with increases in extreme winds [WGI-3]. A rise in mean sea level is largely responsible for an increase in extreme sea level events and stronger storm surges in coastal areas [WGI-3].

Ocean Acidification and Oxygen. The uptake of CO_2 by the ocean has resulted in a gradual acidification of seawater. Long time series from several ocean sites show declines in pH in the mixed layer between -0.0015 and -0.0024 yr^{-1} [WGI-3]. Projections show large 21st century decreases in pH and carbonate ion concentrations (CO_3^{2-}) throughout the world oceans for high-emissions scenarios [WGI-6]. Projections show large 21st century decreases in oceanic dissolved oxygen caused by enhanced stratification and warming, and mainly located in the sub-surface mid-latitude oceans. There is however no consensus on the future evolution of the volume of hypoxic and suboxic waters [WGI-6].

Sea Ice and the Cryosphere. The significant retreat in the extent of Arctic sea ice in all seasons that was documented by AR4 has continued. Since 1979, the end-of-summer extent of Arctic sea ice has decreased by 12% per decade [WGI-4]. In contrast, the total extent of Antarctic sea ice has increased slightly over the same 30-year period, but there are strong regional differences in the changes around the Antarctic [WGI-4]. Overall, CMIP5 models better capture the rapid decline in summer Arctic sea ice observed during the last decades than CMIP3 models, but spread across Arctic sea ice projections remains wide. More than 90% of the CMIP5 models analyzed reach nearly ice-free September conditions in the Arctic by 2100 under RCP8.5 [WGI-12]. In the Southern Hemisphere future changes in sea ice remain highly uncertain [WGI-12]. Reductions in northern hemisphere snow cover extent, permafrost degradation, glacier retreat, and increased surface melt of Greenland are evidence of systematic changes in the cryosphere linked to anthropogenic climate change [WGI-10]. The Arctic region warms most under all scenarios, as in AR4, with a polar amplification factor ranging from 1.8 to 3.3 [WGI-12]. Northern Hemisphere spring snow covered area is projected by 2100 to decrease between 9% (RCP2.6) and 24% (RCP8.5) [WGI-12].

Greenhouse Gases, Pollution, & Radiative Forcing. Land-use, land-use change and land management is emerging as a key driver of the future terrestrial carbon cycle, modulating both emissions and sinks, but this human induced process is not consistently represented in coupled carbon cycle climate models, causing a significant source of uncertainty in future projections of atmospheric CO_2 and climate [WGI-6]. Warming alone will likely increase O_3 in polluted regions, but decrease baseline O_3 levels in surface air [WGI-11]. The sign of the PM response to climate change is uncertain, depending on regional precipitation changes and shifting aerosol components [WGI-11]. The RCPs project much lower emissions of pollutants than do the SRES [WGI-11].

Atmospheric Circulation and Patterns. As the climate warms, the Hadley and Walker circulations are projected to slow down, and the Hadley cell widens giving broader tropical regions and a poleward encroachment of subtropical dry zones [WGI-12]. Changing mean sea level pressure is projected to shift the mid-latitude storm tracks poleward in both hemispheres along with reducing the overall frequency of storms [WGI-12]. Global monsoon precipitation is projected to strengthen in the 21st century with increase in its area affected and its intensity, while the monsoon circulation weakens [WGI-14].

Extreme Weather & Climate. Globally, there is confidence that the length or number of warm spells, including heat waves, has increased since the middle of the 20th century, and this is clearly the case for large parts of Europe [WGI-2]. Consistent with AR4 conclusions, the number of heavy precipitation events (e.g., 95th percentile) has increased significantly in more regions than it has decreased, with strongest evidence in North America [WGI-2]. There continues to be a lack of evidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale [WGI-2]. New results no longer support the AR4 conclusions regarding global increasing trends in droughts since the 1970s [WGI-2]. There is little confidence in basin-scale projections of trends in tropical cyclone frequency and intensity to the mid-21st century [WGI-11]. The magnitude of both high and low temperature extremes is projected to increase faster than the mean, and in most regions a one-in-20 year maximum temperature event will become a one-in-2 year event by the end of the 21st Century under RCP8.5 [WGI-12]. Twenty-first century projections of extreme water levels and waves are based on future storminess in a warming climate using

both dynamical and statistical approaches, but it is difficult to specify regional changes in atmospheric, storm-driven extremes [WGI-13].

Regional Climate Change. Projected climate change in North America will be characterized by a loss of snowpack at high elevations, mid-continental summertime drying, and increasing precipitation over the northern third of the continent [WGI-14]. Projected climate change in South America will be characterized by precipitation increase over southeastern South America, with an increase in extreme precipitation over La Plata basin region and decrease in central Amazonia and northern coast, and an increase in the number of consecutive dry days in northeastern South America [WGI-14]. A significant rainfall decrease across the entire Mediterranean region is projected [WGI-14]. Termination of the rainy season over Japan (Baiu) will be delayed [WGI-14]. Indian Monson circulation is projected to weaken while the total seasonal precipitation increases and the number of rainy days decreases [WGI-14]. A drying trend is projected to continue over southern Australia through the 21st century, and become evident over the north and east of New Zealand [WGI-14]. Precipitation is *likely* to increase in the west of New Zealand in winter and spring [WGI-14].

1.3.4. Working Group III Contribution to the IPCC Fifth Assessment Report

Working Group III of the IPCC is charged with assessing scientific research related to the mitigation of climate change. "Mitigation" is any human intervention to reduce the sources or enhance the sinks of greenhouse gases. Because mitigation lowers the likely effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts—a topic addressed in more detail in this report of WGII. Responding to climate change is ultimately an exercise of risk management that includes both mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, and attitudes about risk. The literature assessed in AR5 also emphasizes the ethics of climate policy, as well as equity considerations, in considerably more detail than AR4.

Since the AR4 (2004 data), global anthropogenic greenhouse gas (GHG) emissions have continued to grow and reached an all-time high of 50.1 Gt CO_2eq in 2010. Despite existing mitigation policies, GHG emissions have grown more quickly between 2000 and 2010 than in previous decades. While CO_2 emission growth from increases in population and per capita income continue to outgrow savings from efficiency improvements, a growing carbon intensity of energy inputs contributed to emission increases for the first time since 1970. At 2010 levels, every 12 years an amount of fossil-fuel related CO_2 is emitted comparable to the total cumulative emissions before 1970 [WGIII-1, WGIII-5].

Regionally, the large majority of CO_2 emission growth over the last decade (2000-2010) has taken place in Asia. Roughly 83% of the CO_2 emission growth between 2000 and 2010 can be attributed to Asia from a territorial and 72% from a consumption perspective. Developing countries (non-Annex B) have overtaken developed countries (Annex B) in terms of their territorial as well as consumption based CO_2 emissions. Average per capita CO_2 emissions of developed countries remain roughly four times higher than of developing countries, even though a growing number of developing countries show per capita GHG emissions in the range of developed countries [WGIII-1, WGIII-5, WGIII-14].

Baseline emission trajectories for fossil and industrial sources from the scenarios literature are inconsistent with a 1.5^{0} or 2^{0} C target as discussed in the international climate change negotiations. The majority of baseline scenarios will exceed atmospheric GHG concentrations of 1000 ppm in 2100 with a likely temperature increase larger than 4^{0}C compared to pre-industrial levels [WGIII-6].

Scenarios meeting a stringent concentration goal of 450 ppm CO_2eq by 2100 with a 60% probability of not exceeding a temperature increase of 2^{0}C are becoming increasingly challenging. The vast majority of scenarios include temporary overshoot of this concentration goal [WGIII-6]. If ambitious stabilization targets such as 450 ppm CO_2eq are to be met, delays in international cooperation on climate change mitigation increasingly require net negative emission in the second half of the 21st century and the large-scale application of carbon dioxide removal technologies (CDR). Most CDR technologies are not mature and attended by a large set of risks. Pathways that are

dependent on the large-scale application of CDR technologies are characterized by increasingly risky profiles through a loss in the ability of policymakers to hedge risks freely across the mitigation technology portfolio [WGIII-6]. The cost of mitigation can affect the ability of society to adapt to climate change. Delays in mitigation not only increase the cost of mitigation, but also they reduce the capacity for adaptation. Some mitigation strategies could substantially increase stressors on water and other natural resources that are also being directly affected by changes in the physical climate system.

A broad body of literature has emerged analysing mitigation choices and societal objectives and non-climate policies that may affect mitigation efforts. Initial evidence from comprehensive models shows that if stringent climate policies are in place, synergistic relationships between societal objectives tend to be stronger and the added costs of any supplementary policies to reach other objectives (energy security/air pollution) at stringent levels can be significantly reduced – particularly in the near term [WGIII-6]. Demand side mitigation options tend to be associated with fewer risks and a larger number of co-benefits than mitigation options on the supply side. Energy efficiency options may therefore provide opportunities to manage risks across the mitigation portfolio and achieve other societal objectives beyond their potential to limit GHG emissions [WGIII-7, WGIII-8, WGIII-9, WGIII-10].

Human decision making is directly affected by the type of uncertainties that prevail. While previous reports have emphasised the uncertainties in the natural system, WGIII AR5 highlights social system uncertainties and suggests that these may be at least of similar magnitude [WGIII-2].

Approaches to international cooperation in climate policies have increased and become more diverse ranging from strong multi-lateralism to harmonized national and regional policies to decentralised architectures that may arise out of heterogeneous regional, national, and sub-national policies [WGIII-13]. Linkages among regional, national, and sub-national programs may complement international cooperation. While policy linkage can take several forms, linkage through carbon markets has been the primary means of regional policy linkage due to the greater opportunities for trade as carbon markets expand. Such forms of regional agreements could then, in principle, form building blocks for greater global cooperation by linking these efforts across regions [WGIII-13, WGIII-14].

The WGIII report further suggests that there is no best policy for mitigation. Different policies play different roles, typically to 1) provide a price signal; 2) remove barriers; or 3) promote long-term investments. A combination of policies that addresses all three roles could be most effective. It may be advantageous to design and adjust policies so as to complement rather than substitute for other policies in the same and other jurisdictions. Appropriate designs depend on national and local circumstances and institutional capacity. These categories are complementary when policy packages are designed to take advantage of synergies and avoid negative interactions. If there is no coordination within an integrated perspective then results in one area may be undone by results in another area for instance through leakage and rebound effects [WGIII-15].

Frequently Asked Questions

FAQ 1.1: What is the information basis for the assessment and how has it changed since the last IPCC report?
IPCC assessment reports are based on the most recent scientific, technical and socio-economic literature produced worldwide relevant to the understanding of climate change. IPCC report authors critically assess the literature and develop a synthesis of current understanding based on that literature. While the majority of the literature they assess is contained in peer-reviewed journal articles and books, IPCC authors can also consider non-published or non peer-reviewed literature sources. The volume of literature available for assessing climate change impacts, adaptation and vulnerability has grown dramatically since the last IPCC assessment report (AR4, 2007) was prepared. The total number of publications on the topic of climate change impacts roughly doubled between 2005 and 2010. The proportion of literature focusing on individual countries within IPCC regions has broadened, particularly for Asia.

FAQ 1.2: How has our understanding of the interface between human, natural and climate systems expanded since the 2007 IPCC Assessment?
Fundamental advances in scientific methods that integrate physical climate science with knowledge about impacts in human and natural systems have enabled a more robust assessment across a greater number of sectors with finer-

scale regional details. Many of the challenging regional impacts of climate change emerge from interacting stresses on people, societies, infrastructure, industry, and ecosystems. These complexities can now be quantitatively described for some systems. A more comprehensive, diverse overview of regional vulnerabilities, impacts and adaptation is made possible with the growth in the assessment-relevant scientific literature for all IPCC regions, including *Open Oceans* [Chapter 30], and by improved coordination with WG I and WG III. This report as a whole reflects substantial expansion of relevant knowledge from the social sciences and increased collaboration among experts on the human dimensions of climate change.

FAQ 1.3: How is the state of scientific understanding communicated in this report?

The body of science on climate change and its impacts has increased greatly over time. Future climate change and its impacts, however, cannot be known exactly. Some uncertainties stem from the possible future paths of socioeconomic development, resulting emissions of greenhouse gases, and associated changes in the exposure and vulnerability of society. Others follow from incomplete understanding of changes in the climate system and also of the societal capacities and challenges for potential responses. Because impacts for human and natural systems depend on how changes in climate and development choices interact, evaluating and implementing response strategies is an exercise in risk management. Importantly, decisionmaking requires judgments beyond the realm of science about what society and stakeholders value. Scientific understanding informs decisionmaking that anticipates, prepares for, and responds to climate change, by providing information about the full range of possible consequences and associated probabilities. In some cases, the probability of an impact occurring may be relatively low, but the consequences of the impact are so important that it warrants consideration. To clearly communicate the state of scientific understanding related to climate change and its impacts, the scientists developing this assessment report use specific terms, methods, and guidance for characterizing their degree of certainty in conclusions.

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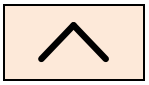
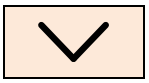
Table 1-1: Observed, attributed, and projected changes in the climate system, including impacts, adaptation, mitigation and vulnerability to climate change.

Phenomenon	Trend	Observed to 2010	Attributed (GHG)	Projected to 21st C.	Fig 1-7 symbol
CO_2	^	****	****	****	
Global Average Surface Temperature	^	****	***	****	
Continental Average Surface Temperature	^	****	**	****	
Global Mean Sea Level (steric)	^	****	***	****	
Arctic Sea Ice	v	**	*	****	
Hot Days and Nights	^	**	**	****	
Cold Days and Nights	v	**	**	****	
Heat Waves	^v		*	**	
Heavy Precipitation Events	^v	*		**	
Drought Frequency or Intensity	^v			*	
Tropical Cyclone Intensity	^				
N. Hemisphere Snow Cover	v	X	X	*	
N. Hemisphere Precipitation	^		X	X	
River Runoff	^		X	X	
			Attributed (Clim.Ch.)		
Extratropical Cyclones move Poleward	^	*		*	
Monsoons Change	~				
Economic Loss from Weather & Climate Extremes	^		X	X	

Table 1-1 Notes: Attribution in the top-half of the table is to human forcing of the climate, primarily through the increase in greenhouse gases (WGI). Attribution in the bottom-half, impacts, adaptation and vulnerability is to the observed local or regional climate change (WGII).

Trend Assessment


Increasing overall

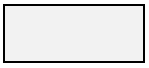

Decreasing overall

More regions increasing than decreasing

More regions decreasing than increasing

No definite trend

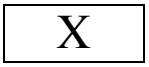
Confidence Assessment


High confidence

Medium confidence

Low confidence

Very low or no confidence



No assessment made

Likelihood Assessment

**** *Virtually Certain* 99% - 100%

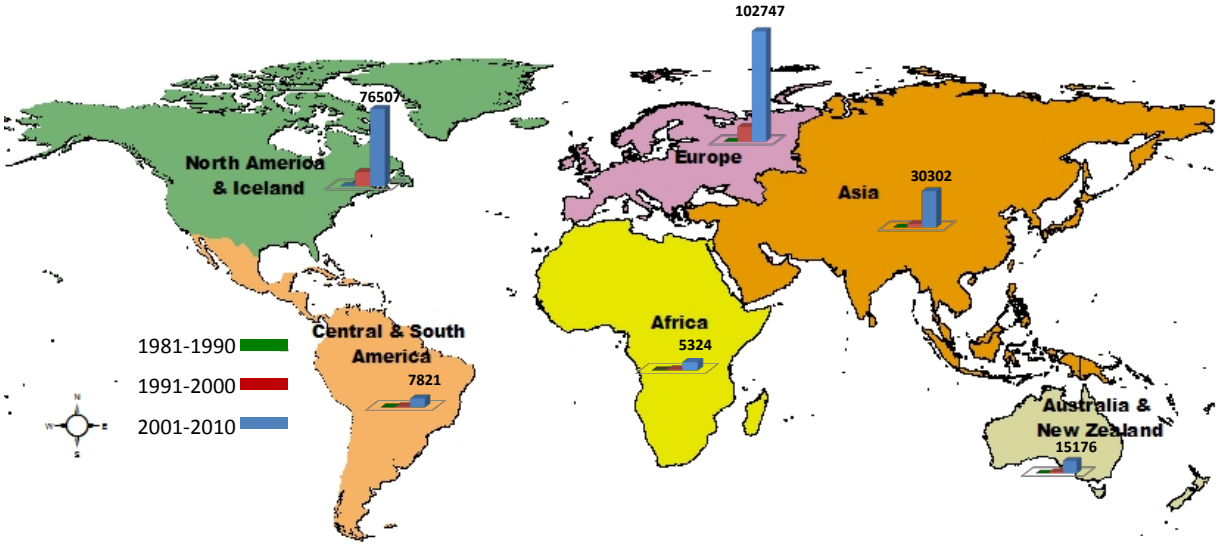
*** *Extremely Likely* 95% - 100%

** *Very Likely* 90% - 100%

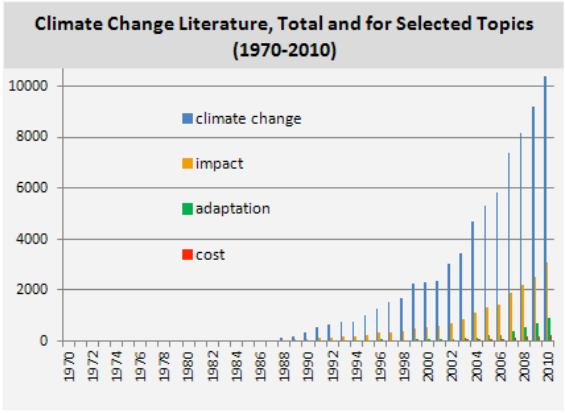
* *Likely* 66% - 100%

Table 1-2: Links between SRREN and the Working Group II contribution to the Fifth Assessment Report.

SRREN findings	WGII-AR5 findings
The sustainability of bioenergy, in particular in terms of lifecycle GHG emissions, is influenced by land and biomass resource management practices (Ch. 9)	Land cover (including forests and agriculture) may be affected by future climate change, which has inferences implications for the potential of these lands to produce biofuels and sequester carbon from the atmosphere (Ch. 19)
The water availability is a critical factor that limits the development of water cooled thermal power and hydropower (Ch. 9)	Climate change is likely to affect future surface and groundwater supplies and the stresses that the development of water-dependent energy resources can have on freshwater ecosystems (Ch. 4)
A wide range of technologies are already available (e.g. wind turbines) or however possible (e.g. barrages for tidal range, submarine turbines for tidal and ocean currents, heat exchangers for ocean thermal energy conversion, etc.) to produce energy from oceans and wind (Ch. 6 and 7)	Ocean currents and wind action could be affected by climate change. Thus, the capacity of these energy technologies should be revised on the basis of future climate conditions (Ch. 6).
Higher energy prices associated with transitions from fossil fuels to renewable energy sources may have adverse effects on local and regional economic and social development (Ch. 9)	The challenge for climate-resilient pathways is to identify and implement mixes of technological options that reduce net carbon emissions and at the same time support sustained economic and social growth (Ch. 20)
Latin America is second to Africa in terms of technical potential for bioenergy production from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands (Ch. 9)	In large countries of Latin America the production of bioenergy requires large areas for agriculture determining environmental degradation and strong economic teleconnections (e.g. economic growth of giant consumers as China) (Ch. 27)
Central and South America are second to Asia in terms energy generation in the world, displaying a 20% share of total annual generation. The quality of water resources availability is the largest in the world with an average regional capacity factor of over 50%. As a result, the region has by far the largest proportion of electricity generated through hydropower facilities (Ch. 5)	Hydropower is the main source of renewable energy available in Central and South America, but it is also affected from potential impacts of climate change (Ch. 27)



(a)



(c)

Climate Change Literature by Region (Title, Key Words, or Abstract)

	1981-1990	1991-2000	2001-2010
Africa	0	509	4815
Asia	9	2821	27472
Europe	71	12218	90458
North America	290	11926	64281
Central and South America	2	677	7142
Australia and New Zealand	7	1654	13515

(d)

Search Words (translated)	Language	1981-1990	1991-2000	2001-2010
"Climate change"	English	990	12686	61485
	Chinese	1454	6353	22008
	French	1	108	815
	Russian	67	210	1443
	Spanish	3	82	1381
"Climate change" and "adaptation"	English	14	373	3661
	Chinese	6	58	321
	French	0	7	110
	Russian	0	7	44
	Spanish	0	5	103
"Climate change" and "impacts"	English	232	3001	16218
	Chinese	133	515	1780
	French	0	1	95
	Russian	0	72	403
	Spanish	0	7	103
"Climate change" and "cost"	English	24	699	4099
	Chinese	1	22	162
	French	0	7	36
	Russian	0	1	24
	Spanish	0	2	11

Figure 1-1: Results of English literature search using the Scopus bibliographic database from Reed Elsevier Publishers. (a) Annual global output of publications on climate change and related topics: impacts, adaptation,

human health, and costs (1970-2010). (b) Country affiliation of authors of climate change publications summed for IPCC regions for three time periods: 1981-1990, 1991-2000, and 2001-2010, with total number during the period 2001-2010. (c) Results of literature searches for climate change publications with individual countries mentioned in publication title, abstract or key words, summed for all countries by geographic region. The following individuals conducted the literature searches: Valentin Przyluski (French), Huang Huanping (Chinese), and Peter Zavialov and Vasily Kokore (Russian), and Saúl Armendáriz Sánchez (Spanish). (d) Number of publications in five languages that include the words "climate change" and "climate change" plus "adaptation", "impacts" and "cost" (translated) in the title, abstract or key words during the three time periods.]

Figure 1-2: Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The First Assessment Report (FAR, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change, but for the Second Assessment Report (SAR 1996) the WGII contribution included mitigation and adaptation with the impact assessment. With the TAR (2001) and subsequent assessments, mitigation was addressed by IPCC Working Group III. Since the TAR, WG II has focused on impacts, adaptation and vulnerability with an expanded effort on the regional scale.

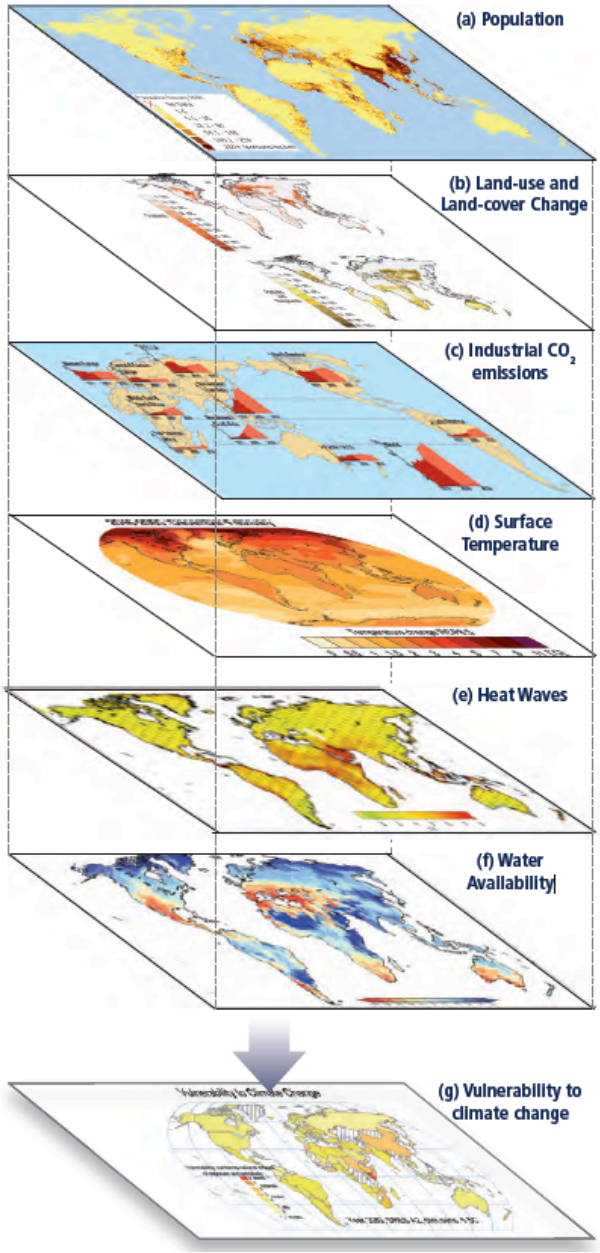


Figure 1-3. Examples of the diversity and global heterogeneity of the many stressors related to climate change impacts, adaptation, and vulnerability: (a) Population, (b) Land-use and land-cover change, (c) Industrial CO_2 emissions, (d) Surface temperature change, (e) Heat waves, (f) Water availability, and (g) Vulnerability to climate change. Sources: (a) Global population density for year 2000 from the LandScan project at Oak Ridge National Laboratory and CIESIN, Columbia U. (http://sedac.ciesin.columbia.edu/data/collection/gpw-v3/maps); (b) Croplands and pasture/rangeland coverage from Foley *et al.* (2005); (c) Industrial sector energy/electricity-related CO_2 emissions ($GtCO_2$) for 1971-2000 (historical) and 2001-2030 (SRES B2) (AR4 WGIII TS.18 and Table 7.1, 7.2). EECCA = Countries of Eastern Europe, the Caucasus and Central Asia; (d) Surface temperature change projected for Dec-Jan-Feb, years 2046-2065 minus 1986-2005 under RCP8.5 from CMIP5 median (AR5 WGI Annex I); (e) Heat extremes based on Warm Spell Duration Index increase from 1980-1999 to 2081-2100 under SRES A2 normalized by standard deviation (SD) (SREX; after Fig.5 of Orlowsky and Seneviratne, 2011); (f) Water availability based on projected change of annual runoff (%) from 1981-2000 to 2081-2100 for SRES A1B (AR4 WGII Fig. 3.8, based on CMIP3); (g) Vulnerability to climate change in year 2050 (SRES A2, climate sensitivity 5.5°C, adapted from AR4 WGII Fig TS.19, 20.6).

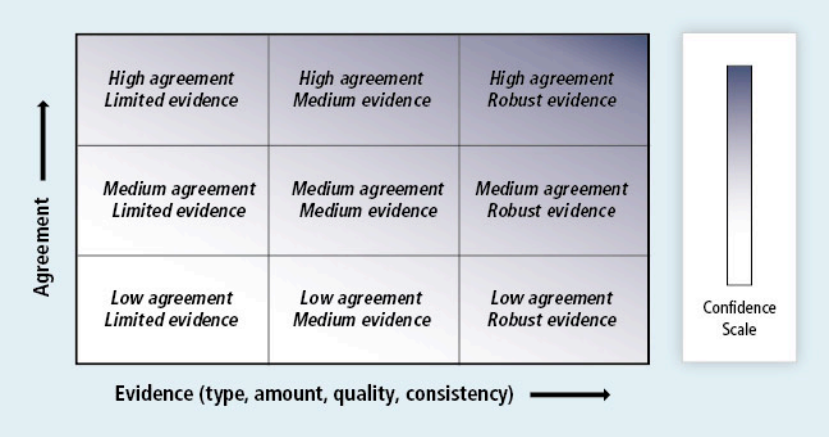


Figure 1-4: Evidence and agreement statements and their relationship to confidence. The shading increasing towards the top-right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

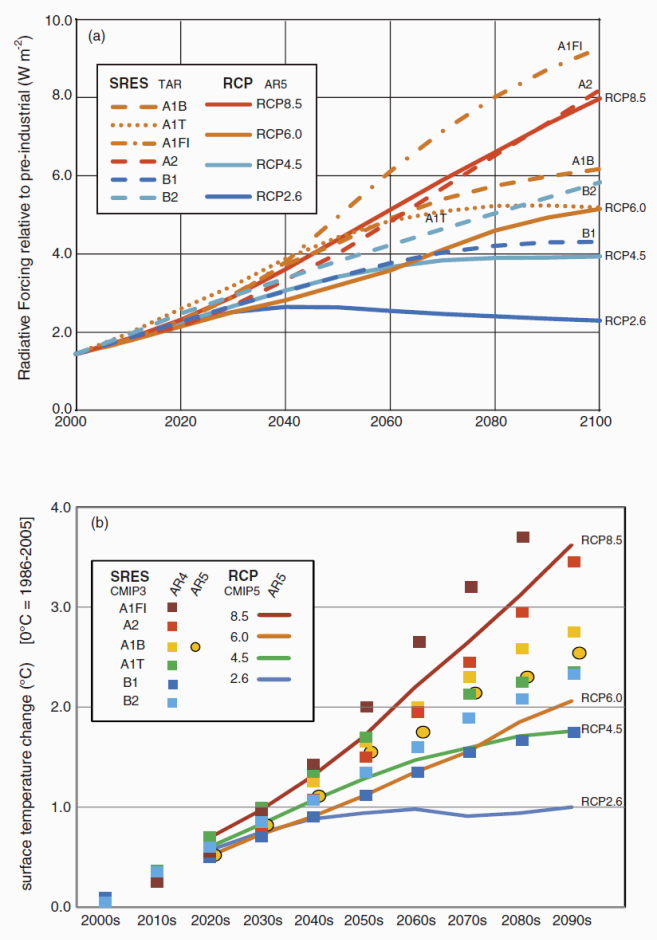


Figure 1-5: (a) Projected RF (W m-2) and (b) global mean surface temperature change (°C) over the 21st century from the SRES and RCP scenarios. RF for the RCPs are taken from their published CO2-eq (Meinshausen et al., 2011), and RF for SRES are from the TAR Appendix II (Table II.3.11). Comparable models are used in both RF calculations. The SRES RF are shifted upward by 0.12 W m-2 to match at year 2000. Temperature changes are

decadal means based on the model ensemble mean CMIP5 data for the RCPs (see AR5 WGI Chapters 11, 12, Annex II tables). The same analysis applied to CMIP3 SRES A1B is also shown (yellow circles). The SRES temperatures (colored squares, AR4 WGI Figure 10.26) are based on a simple climate model tuned to the CMIP3 models. Thus the yellow circles and yellow squares differ by a few tenths °C.

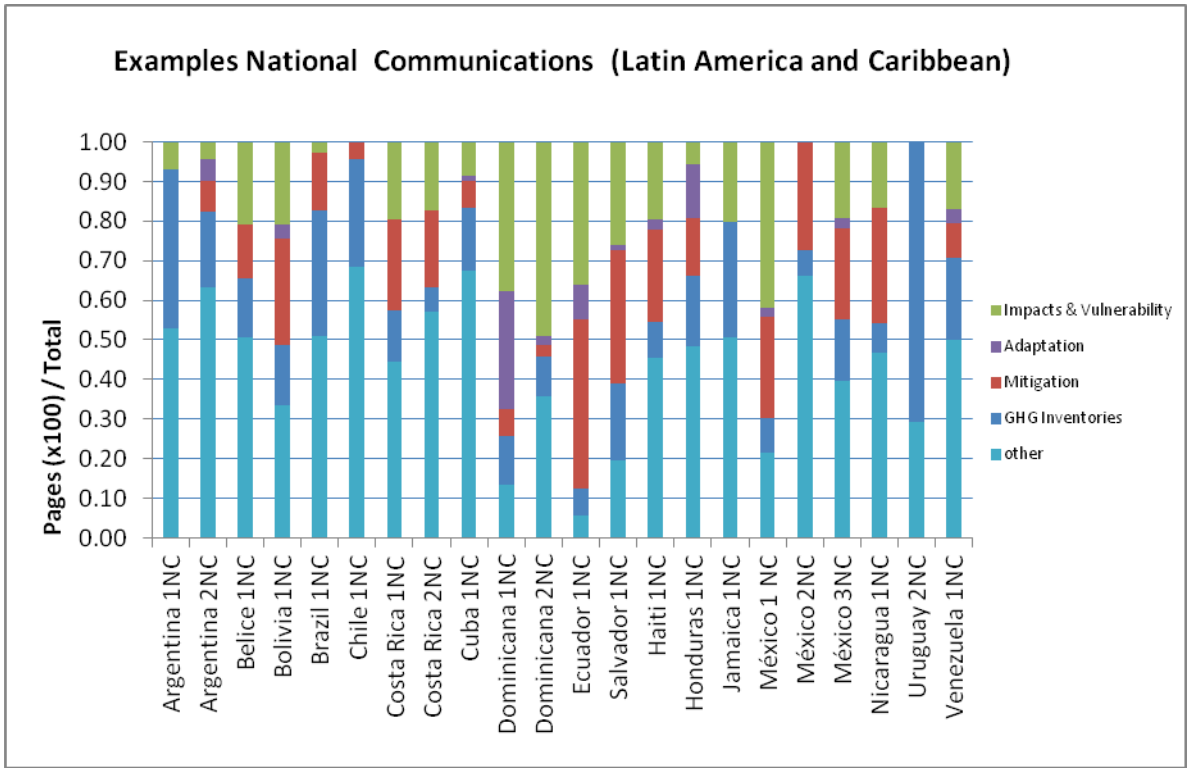


Figure 1-6: Distribution of topics related to impacts and vulnerability, adaptation, mitigation and greenhouse gas inventories (GHG Inventories) in the First (1), Second (2) or Third (3) National Communications (NC) of several Latin American and Caribbean countries (Argentina, Belize, Bolivia, Brazil, Chile, Costa Rica, Cuba, Dominica, Ecuador, El Salvador, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Uruguay and Venezuela). Documents source: http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.phpUNFCCC.

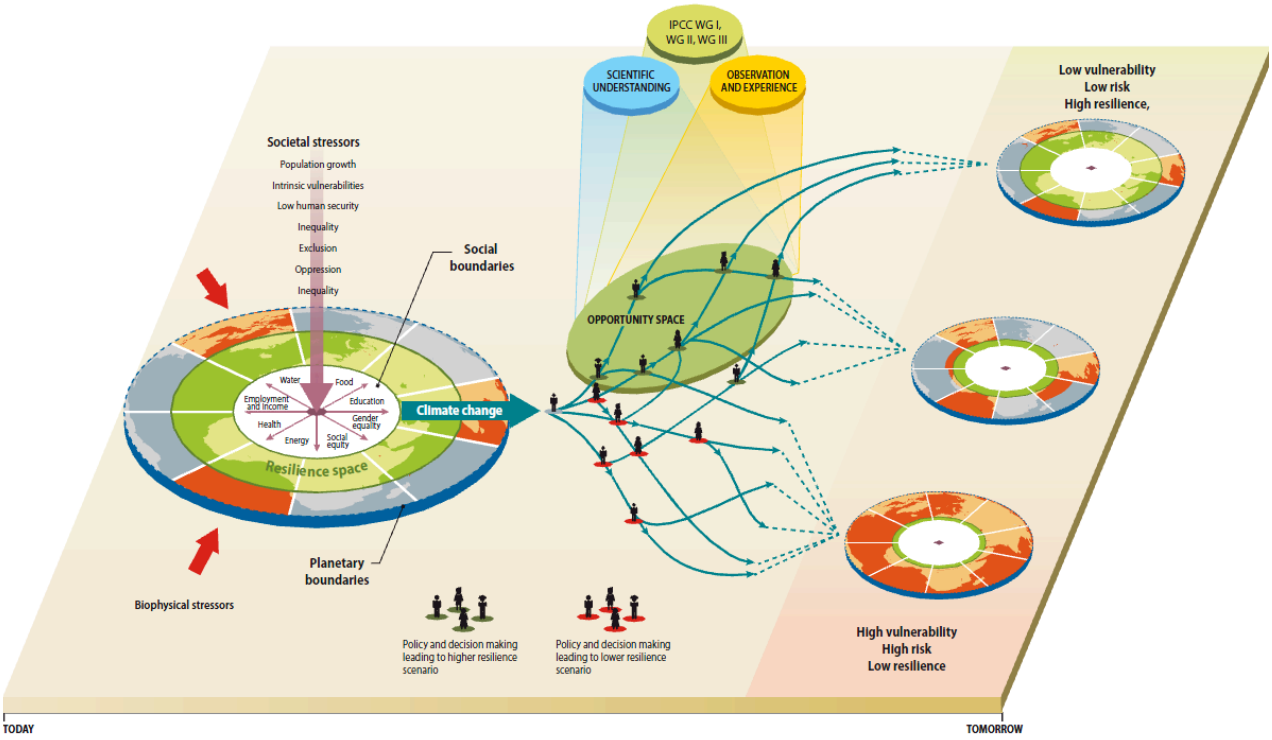


Figure 1-7: Conceptual framework for assessing interactions between biophysical and societal stressors that impact the resilience of natural and human systems today and in the future. Actions, including climate change adaptation and mitigation, taken in the opportunity space lead to a diverse range of pathways and outcomes – toward a future of high risk, high vulnerability and low resilience space or toward a future of low risk, low vulnerability and high resilience space.

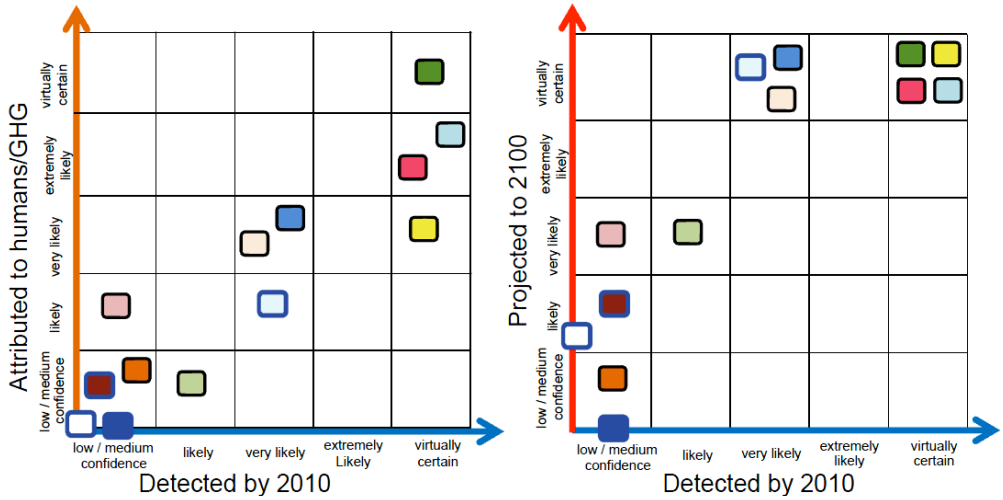


Figure 1-8: Climate change and its impacts detected to date (horizontal axis) is plotted against (left panel) attribution of those changes to greenhouse gases and (right panel) projection of those changes into the 21st century for a global warming exceeding 2°C. Only phenomena with a detection, attribution or projection at high confidence levels or with quantifiable uncertainty are shown. All phenomena are defined in Table 1-1 where the color coded symbols and likelihood are defined. Results are taken from the AR4, SREX, and AR5 WGI, but primarily from WGI because the attribution is to the observed increase in greenhouse gases that has driven anthropogenic climate change, rather than as in WGII to the regional/local observed warming. For AR5 WGII results, see inter alia Chapters 18 and 19.

Chapter 2. Foundations for Decision-Making

Coordinating Lead Authors
Roger N Jones (Australia), Anand Patwardhan (India)

Lead Authors
Stewart Cohen (Canada), Suraje Dessai (UK), Annamaria Lammel (France), Rob Lempert (USA), Monirul Mirza (Bangladesh/Canada), Hans von Storch (Germany)

Contributing Authors
Werner Krauss (Germany)

Review Editors
Rosina Bierbaum (USA), Nicholas King (South Africa)

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References

Executive Summary

The purpose of this chapter is to offer foundational knowledge and important perspectives on how better decisions can be made in response to assessments of climate impacts, adaptation and vulnerability. [2.1.1] It introduces new material from a range of disciplines, broadening the decision-making methods used to date. In the past, IPCC-sponsored assessment methods and policy advice have been framed by the assumption that better science will lead to better decisions. [2.1.2] While better science is necessary, it is not sufficient, requiring additional decision-support processes and tools. [2.1.2, 2.2] The decision-sciences applied on scales from the individual to organizations to institutions provide a great deal of decision-making theory and practice that can inform process and methods. [2.2, 2.3]

All decisions involving uncertainty and valued outcomes involve risk management. [2.1.1] The international risk management standard defines risk as *the effect of uncertainty on objectives*. Risk management provides a useful framework for most CCIA decision-making. [2.1] A broad operational definition of risk is *a situation or an event where something of human value (including humans themselves) is at stake and where the outcome is uncertain*. [2.1.1]

Iterative risk management involves an ongoing process of assessment, action, reassessment, and response that may need to be applied under climate change, for decades, if not longer. [2.1.2, 2.3.1] Both the objective and subjective aspects of risk: 1) calculated risks derived through formal processes and 2) perceived risk, the subjective view of risk held by a stakeholder, need to be incorporated into the decision-making process. [2.1.2] In simple systems, calculated and perceived risks are more likely to be closely aligned. Complex decision-making contexts will require both the risks of various future outcomes and the risks of alternative actions to be assessed. [2.3.1] This places significant demands on people and organisations to manage that process within the context of their own aims. [2.3.1]

Scenarios are a vital part of managing uncertainty. They can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration). [2.2.1.1] Historically, most scenarios used for CCIAV assessments have involved the former type. The new RCP scenario process is being constructed to cater for both problem and solution framing. [2.2.1.1]

Most social-ecological systems where adaptation takes place are reflexive, requiring the development of adaptive management techniques such as iterative risk assessment. In reflexive systems, decisions that are implemented will change the system itself, demanding ongoing monitoring and assessment in order to track those changes, as they are rarely predictable. [2.2.1.1] Formal processes of monitoring and periodic review, including revisiting ongoing aims and objectives, are required to support adaptive management. [2.2.1.3]

Decision-making on CCIAV has a very strong ethical basis that is expressed at a range of institutional scales and is strongly embedded into elements of risk governance on those scales. [2.2.2.1, 2.2.2.2, 2.2.3.4]

Decision support is situated at the intersection of data provision, expert knowledge and human decision-making at a range of scales from the individual to the organization and institution. Decision support is defined as a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use. [2.2.1, 2.2, 2.3] Such support is most effective when it is context-sensitive, taking account of the diversity of different types of decisions, decision processes, and constituencies. [2.3.1, 2.3.3, 2.3.4] Institutionally, boundary organisations are important in translating and transferring these messages. [2.3.1, 2.3.2]

Climate services aim to make knowledge about climate regionally accessible to a wide range of decision makers. [2.3.3] In doing so they have to consider information supply, knowledge competition and user demand.

Knowledge transfer is a negotiated process that can take a variety of cultural values, orientations and alternative forms of knowledge into account. [2.3.1, 2.3.3]

Climate change response can be linked with sustainable development through actions that enhance resilience, which is the capacity to absorb shocks and to change in order to maintain the same identity. Sustainable adaptation, disaster risk management, and new types of governance and institutional arrangements are being studied for their potential to support the goal of enhanced resilience. [2.4.2]

Transformation can be managed through transitional arrangements but these are notoriously difficult to control and are best managed through adaptive management or similar process. [2.4.3]

2.1. Introduction and Key Concepts

2.1.1. Decision-Making Approaches in this Report

This chapter addresses the foundations of decision-making with respect to climate change impact, adaptation and vulnerability (CCIAV) assessment. The Fourth Assessment Report (AR4) summarized methods for CCIAV (Carter et al., 2007), which we build on by surveying the broader academic literature to obtain knowledge on decision-making suitable for CCIAV. This expanded focus reflects the evolution of CCIAV assessments from the straightforward linear scenario-driven approaches described in the early literature to the wide range of decision-making approaches active today.

The overarching theme of the chapter is risk management. The International Standard ISO:31000 defines risk as *the effect of uncertainty on objectives* (ISO, 2009) and Rosa (2003) defines it as *a situation or an event where something of human value (including humans themselves) is at stake and where the outcome is uncertain*. Because all decisions on CCIAV are affected by uncertainty and involve valued objectives, all are decisions of risk (e.g., Giddens, 2009). To encompass both this broad theme and the specific nature of many kinds of decision-support, a three-tier hierarchy for decision-making is presented: approach, methodology and method (Figure 2-1). Approach describes the broad framing and scoping of an issue; methodology comprises the principles and rules governing the decision-making process; and that process is applied using methods and tools.

[INSERT FIGURE 2-1 HERE
Figure 2-1: Risk portrayed as an approach, methodology and method using definitions relevant to this report.]

Risk management frames the overall chapter approach, but at the methodological scale can be applied in many ways: e.g., financial, disaster, engineering, environmental and health risk. A range of different tools and methods can be applied to each methodology. Many other methodologies such as vulnerability, resilience and livelihood assessments may at first seem to be unconnected with traditional risk assessment, but may in fact be analysing, evaluating or managing risks within a larger risk management process. For example, developing resilience can be seen as managing a range of potential risks; sustainable development aims to developing a system robust to risks informed by values-based processes and outcomes.

The Fourth Assessment Report endorsed risk management as a suitable decision-support framework for CCIAV assessment because it offers formalized methods for addressing uncertainty, involving stakeholder participation, identifying potential policy responses, and evaluating those responses (Carter et al., 2007; Yohe et al., 2007). A risk management framework also facilitates the mainstreaming of climate-centric decision-making into broader decision-making processes. The AR4 report also summarized advances in many CCIAV assessment approaches and described how they can fit into a risk management framework. The literature shows significant advances on all these topics since AR4 greatly expanding methodologies for assessing impacts, adaptation and vulnerability in a risk context (Agrawala and van Aalst, 2008; Hinkel, 2011; Jones and Preston, 2011; Preston et al., 2011).

A major aim of risk management is to make better decisions. There are many definitions of decision in the literature but all involve choosing amongst alternatives, and some involve a course of action to enact that decision. **But what**

constitutes a "better" decision? *A better decision is one where the process of decision-making is judged to produce more acceptable outcomes within a given set of circumstances than previous decisions*. It may be highly precautionary, designed to avoid the worst possible outcomes (Hansson, 2006; Malik et al., 2010). Elwyn and Miron-Shatz (2010) argue that process be given more weight than outcomes under uncertain futures where many outcomes are possible. Many factors that influence how a decision can be assessed include: who is making the decision, its context and purpose, what information is used, who implements its actions, the resources invested in the decision-making process, the choice of method, who is affected by its outcomes, how those outcomes are valued and assessed over a given time horizon, and the extent to which the objectives being pursued are regarded as appropriate. Section 2.2.3.4 shows that ethics are an important aspect of such choices.

Two aspects of decision-making that distinguish climate change from most other contexts are the long time scales involved and pervasive uncertainties (Kandlikar et al., 2005; Ogden and Innes, 2009; Lempert and McKay, 2011). These uncertainties include not only future climate but also socio-economic change and potential changes in norms and values across generations. Process uncertainties also affect the choice of the most suitable decision-support applications for managing specific problems or seeking uncertain solutions within a given context.

Decision-makers range from individuals, to organizations to institutions, at the largest scale comprising systems of systems. Decision-makers are influenced by both individual and group factors, such as internal psychological and cognitive factors, their physical and socio-cultural environments, and the institutions within which they operate. They draw from a knowledge base and utilize a variety of methods and tools that they know and accept. Decisions are framed by aspirations and goals and informed by scenarios of how the future may play out.

The study of human reasoning has a long history, in eastern and western traditions and in widespread indigenous cultures. In recent decades, research describing the actual processes of human decision-making, note that the normative (the decision one should arrive at) and descriptive/positive (what people actually do) aspects often diverge (e.g., Raïffa et al., 2002). For example, people often fail to take simple preparations for disasters such as earthquakes or floods even when they have sufficient resources to do so and would, upon more careful reflection, come to believe that they should (McClure et al., 1999; McIvor and Paton, 2007). People may also act inconsistently with a particular formal analysis because they have values and goals not well represented in that analysis (Davies and Walters, 1998; Helsloot and Ruitenberg, 2004).

Previous assessments have described the methods and tools used for decision support, giving less regard to decision-making processes (Carter et al., 1994; Parry and Carter, 1998; Carter et al., 2001; Hulme and Mearns, 2001; Carter et al., 2007; IPCC-TGICA, 2007). Much method development has aimed for objectivity, often assuming that rational knowledge will induce 'rational' behavior. However, the decision sciences literature makes clear that people make decisions based on a whole variety of criteria (Karvetski et al., 2009; Tryhorn and Lynch, 2010); for example, stakeholder groups in a single region show multiple preferences for coastal protection leading to very different solutions for the same hazard (Mustelin et al., 2010). To date, the socio-cultural and cognitive-behavioural aspects of CCIAV decision-making have largely been restricted to descriptions of social learning processes; e.g., Section 2.3.2 on stakeholders in Carter et al. (2007). However, we see these factors as being just as important as specific knowledge brought into the decision-making process.

The next section (2.2) describes diverse aspects important to a full understanding of CCIAV decision making, including methods, tools, and processes (Sect 2.3.1); institutional (2.3.2); and social (2.3.3) contexts. Section 2.3 describes how understanding of these aspects can be used to improve decision making. Section 2.4 addresses the interaction between adaptation and mitigation, sustainable development and transformation.

2.1.2. Iterative Risk Management

Complexity is an important attribute for framing and implementing decision-making processes *[High confidence]*. Simple, well-bounded contexts involving cause and effect can be addressed by straightforward linear methods. When complex contexts interact with human values they become associated with wicked problems. Wicked problems are not well bounded, they are framed differently by various actors and groups, they harbour large

scientific to existential uncertainties and have unclear solutions and pathways to those solutions (Rittel and Webber, 1973; Australian Public Service Commission, 2007). Such 'deep uncertainty' cannot easily be quantified (Dupuy and Grinbaum, 2005; Kandlikar et al., 2005). One important attribute of complex systems is reflexivity, where cause and effect feed back into each other. For example, actions taken to manage a risk will affect the outcomes, requiring iterative processes of decision-making. Under climate change, risks will also change with time (Ranger et al., 2010)

The CCIAV literature has increasingly adopted an iterative risk management framework (Carter et al., 2007; Yohe et al., 2007; Jones and Preston, 2011), which is also consistent with risk governance (Renn, 2008) and a wide range of approaches for structured decision-making involving process uncertainty (Ohlson et al., 2005; Wilson and McDaniels, 2007; Ogden and Innes, 2009; Martin et al., 2011). Iterative risk management involves an ongoing process of assessment, action, reassessment, and response (Kambhu et al., 2007; IRGC, 2010) that will continue – in the case of many climate-related decisions – for decades if not longer (Committee on America's Climate Choices National Research Council, 2011).

Two levels of iteration can be recognised within the iterative risk management process, two internal and one external (Figure 2-2). One internal iteration occurs during the assessment stage and addresses the interactions between the problem, proposed solutions and system feedbacks where managing risk feeds back into the risk itself. A second internal iteration occurs during the management stage following implementation when formal monitoring and review tracks how the system responds and reacts accordingly. The third iteration covers the entire process when an assessment has finished and the decision process returns to the scoping phase.

[INSERT FIGURE 2-2 HERE
Figure 2-2: Iterative risk management framework showing two loops in the assessment process, looking at system feedbacks on options and at the risk management stage where a decision is made and implemented. Adapted from Willows and Connell (2003).]

Idealised, Calculated, Perceived Risks

In complex situations, socio-cultural and cognitive-behavioural contexts become central to decision-making. This requires combining the scientific understanding of risk with how risks are framed and perceived by actors and institutions (e.g., Hansson, 2010). For that reason, formal risk assessment is moving from a largely technocratic exercise carried out by experts to a more participatory process of decision support (Fiorino, 1990; Pereira and Quintana, 2002; Renn, 2008), although this process is proceeding slowly (Christoplos et al., 2001; Pereira and Quintana, 2002; Bradbury, 2006; Mercer et al., 2008).

Earlier applications of risk involved the calculation of hazard × likelihood or probability and consequence, and communicated the results to decision-makers, similar to the way that early CCIAV assessments were carried out. More recent applications have moved from the objective analysis of risk to addressing values at risk and the governance of risk (Power, 2007; Renn, 2008), although hazard-based methodologies remain important when the hazard is the primary concern. Likewise CCIAV methods are expanding from a direct focus on specific climate risks to more mainstream settings where the management of climate risks is integrated with other areas of risk management (Hellmuth et al., 2011). For example, climate risks affecting a local government area will have planning, legal, financial, health and community aspects (Measham et al., 2011). Mainstreaming may require trade-offs between climate and other risks (Kok and de Coninck, 2007; Eakin et al., 2009).

Different epistemologies, or 'ways of knowing' exist for risk (Hansson, 2004; Althaus, 2005; Hansson, 2010), vulnerability (Weichselgartner, 2001; O'Brien et al., 2007) and adaptation assessments (Adger et al., 2009) affecting the way they are framed by various disciplines and are also understood by the public (Garvin, 2001; Adger, 2006; Burch and Robinson, 2007). These differences have been nominated as a source of widespread misunderstanding and disagreement. They are also used as evidence to warn against a uniform epistemic approach (Hulme, 2009; Beck, 2010), a critique that has been levelled against previous IPCC assessments (Hulme and Mahony, 2010).

The following five types of risk have been nominated as important epistemological constructs (based on Thompson, 1986; Althaus, 2005; Jones, 2012):

1) Idealized risk: the conceptual framing of the problem at hand. For example, dangerous anthropogenic interference with the climate system is how climate change risk is idealized within the UNFCCC.
2) Calculated risk: the product of a model based on a mixture of historical (observed) and theoretical information. Frequentist or recurrent risks often utilize historical information whereas single-event risks may be unprecedented, requiring a more theoretical approach.
3) Subjective risk: the mental state of an individual who experiences uncertainty or doubt or worry as to the outcome of a given event. Gives rise to:
4) Perceived risk: the rough estimate of an idealized risk derived informally by individuals and groups.
5) Observed risk: the risk observed once an event is realized. This will update to conceptualization of future risks.

These different types show risk to be partly an objective threat of harm and partly a product of social and cultural experience (Kasperson, 1992; Rosa, 2008). The aim of calculating risk is to be as objective as possible, but the subjective nature of idealized and perceived risk reflects the division between positivist (imposed norms) and constructivist (derived norms) approaches to risk from the natural and social sciences respectively (Demeritt, 2001; Hansson, 2010). Idealized risk will follow both formal and informal pathways through the assessment process. Acceptance of the science behind controversial risks is strongly influence by social and cultural influences (Leiserowitz, 2006; Kahan et al., 2007; Brewer and Pease, 2008); Figure 2-3). Risk perceptions can be amplified socially where events pertaining to hazards interact with psychological, social, institutional, and cultural processes in ways that heighten or attenuate individual and social perceptions of risk and shape risk behaviour (Kasperson et al., 1988; Renn et al., 1992; Pidgeon et al., 2003; Rosa, 2003; Renn, 2011).

[INSERT FIGURE 2-3 HERE
Figure 2-3: Schema for the chapter, showing a hierarchy of decision-makers in the centre and broad groupings of subjects addressed in the chapter. The decision-making environment is described by adaptation, mitigation and sustainable development, the methods and tools utilised include scenarios, decisions are made in the human context of individuals to groups and decisions can be assessed to measure varying degrees of success.]

Understanding of how these perceptions resonate at an individual and collective level can help overcome constraints to action (Renn, 2011). Science is most suited to calculating risk in areas where it has predictive skill and will provide better estimates than may be obtained through more arbitrary methods (Beck, 2000), but an assessment of what is at risk needs to be generally accepted by stakeholders. Therefore, the science always sits within a broader social setting, often requiring a systems approach where science and policy are investigated in tandem, rather than separately (Pahl-Wostl, 2007; Ison, 2010).

Despite there being a literature on the sociology of science relevant to climate change risks (Jasanoff, 1996; Demeritt, 2001; Wynne, 2002; Demeritt, 2006) only recently are these approaches being built into CCIAV assessments. The different types of risk listed above give rise to complex interactions between formal and informal knowledge that cannot be bridged by better science or better predictions but require socially mediated processes of engagement *[medium confidence]*, as discussed in later sections. Idealised risk is important for framing and conceptualising risk. Calculated risk covers the analytic side of risk that concentrates on quantitative decision analysis. Perceived risk is closely aligned with socially constructed risk that emerges from the psychological and behavioural sciences and from social sciences literatures such as anthropology, geography, ethics, sociology, political science, and other.

A large literature describes best practice methods for incorporating and communicating information about risk and uncertainties into decisions about climate change (Climate Change Science Program, 2009; Pidgeon and Fischhoff, 2011). This literature suggestions that effective communication of uncertainty requires products and processes that: i) closes psychological distance, explaining why is this information is important to the recipient; ii) establishes self-agency, explaining what the recipient can do with the information; iii) recognizes that each person's view of risks and opportunities depends on their values; iv) recognizes that emotion is a critical part of judgment; and v) provides mental models that help recipients to understand the connection between cause and effect. In addition, this literature

emphasizes that information providers need to test their messages, since they may not be communicating what they think they are.

2.2. Aspects of Decision-Making

This section surveys aspects of decision-making important to understanding and improving CCIAV decisions. It begins (Section 2.2.1) with a survey of methods, tools, and processes potentially useful for improving such decisions. This literature emphasizes the importance of the organizational and cultural/psychological contexts of decision-making, which are addressed in Sections 2.2.2 and 2.2.3.

2.2.1. Methods, Tools, and Processes for Climate-Related Decisions

Since the AR4, the level of adaptation activity among organizations worldwide has increased substantially (Preston et al., 2009). This activity has delivered substantial experience on which practitioners can draw, as well as expanded needs and opportunities for research. This experience suggests that those faced with CCIAV decisions often require systematic methods, tools, and processes for effective risk management because the challenges they face are complex, complicated, and novel (whether or not the challenges had such attributes before climate change, they certainly do with climate change).

The heterogeneous field of decision sciences integrates 'abstract' decision theory with economic applications, cognitive psychology, and philosophy of action, theoretical computer science or neuroscience. It represents complementary links between cognitive psychology and economics and, more generally, cognitive sciences and social sciences (Kleindorfer et al., 1993; Buchanan and O'Connell, 2006).

Extensive evidence from the decision sciences shows that good scientific and technical information alone is rarely sufficient to result in better decisions *[high confidence]*. Better decisions result from effective decision-making processes that include access to appropriate scientific and technical information but also pay attention to institutional and organizational contexts. Based on the limited experience to date, there may now exist a sufficiently rich set of available methods, tools, and processes to support effective CCIAV decisions in a wide range of contexts *[medium confidence]*.

The concept of *decision support* provides a useful framework for understanding how risk-based concepts and information can help enhance decision-making (see McNie, 2007; National Research Council (US) Panel on Design Issues for the NOAA Sectoral Applications Research Program et al., 2007; Moser, 2009; Romsdahl and Pyke, 2009; Kandlikar et al., 2011; Pidgeon and Fischhoff, 2011). The concept also helps situate methods, tools, and processes intended to improve decision-making within appropriate institutional and cultural contexts.

Decision support is defined as "a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use" (National Academy of Sciences, 2009). Information is decision relevant if it yields deeper understanding or a choice or, if incorporated into making a choice, yields better results for decision makers and their constituents. These definitions, and criteria that can be used to judge the effectiveness of decision processes and decision support, are drawn from surveys of scientific communication and decision-making in many literatures, including public health, hazards management, natural resource management, environmental management and policy-making, land use planning, environmental risk communication, sustainability science, local air quality, as well as climate change mitigation and adaptation (National Academy of Sciences, 2009).

2.2.1.1. Treatment of Uncertainties (including Scenarios)

Methods and tools for addressing uncertainty are often central to risk management and effective CCIAV decision-making. Whether embodied in formal analyses or in the training and habits of decision makers, appropriate uncertainty frameworks are often needed because unaided human reasoning can produce mismatches between

actions and goals under conditions of uncertainty (Kahneman, 2011). The literature also emphasizes the importance of quantifying uncertainty, because merely verbal descriptions can prove ambiguous and often fail to provide the information necessary to adjudicate trade-offs. Adopting frameworks for considering and quantifying uncertainty raises both technical challenges as well as those of organizing uncertain information so that it proves useful within a specific decision support process.

As one key aspect of these challenges, the literature recognizes a wide range of different types of uncertainty. Knight (1921) first contrasted as the difference between well-characterized risks and more poorly-understood, unquantifiable uncertainties. AR4 (Box 2-1) provides a taxonomy of characterizations of the future that distinguishes comprehensiveness, the degree to which a representation captures the full range of socio-economic and biophysical factors, and plausibility, the extent to which a future is possible and to which a probabilistic description can be ascribed (Carter et al., 2007). Recent taxonomies focus on both the level and location of uncertainty (Kwakkel et al., 2010). While the literature provides no consensus on definitions of such levels, in general uncertainty can range from shallow or well-characterized -- in which alternative futures can be specified and probabilities distributions placed over those futures with high confidence -- to deep uncertainty, severe, or extreme uncertainty -- in which not all alternative futures can be specified (that is, surprise is plausible) and probability distributions cannot be specified with confidence. These levels correspond to the confidence scale in the IPCC uncertainty guidance (Mastrandrea et al., 2010). For this assessment, the use of qualitative confidence levels (instead of quantitative) based on expert judgement determined through authors' evaluation of the evidence and levels of agreement, is recommended (Mastrandrea et al., 2010). In model-based analyses, uncertainty can be located in the specification of the system boundary, the conceptual model, the available data, and in different models used to represent the system in question. Both the level and location of uncertainty can affect the appropriate choice of methods and tools in a particular decision context.

_____ START BOX 2-1 HERE _____

Box on scenario building process developed with Chapter 21 regional context – forthcoming.

_____ END BOX 2-1 HERE _____

In recent years the literature has begun to describe two distinct processes for including uncertainty in decision support (Weaver et al., 2012). One process seeks to describe uncertainty as distinct information, independent of other parts of the decision problem. Probabilistic descriptions often take this approach, which follows the assess risks, identify options, evaluate trade-offs loop in Figure 2-2. For instance, probabilistic climate projections are generated to support a wide range of decisions, and thus not tied to any specific choice. In engaging with decision makers, information providers seek to understand what data would prove most useful, for instance temperature and precipitation time series at some level of spatial and temporal resolution, and then seek to provide that data to a wide community of decision makers. The basic structure of IPCC Assessment Reports also follows this pattern, with WGI laying out what is known and uncertain about current and future changes to the climate system. Working Groups II and III then describe impacts resulting from and potential policy responses to those changes. As one advantage, this process promotes a perception of objectivity because those who characterize uncertainty are functionally and often organizationally independent of those who use the uncertainty estimates to make decisions.

In contrast to this 'predict-then-act' process, a second approach seeks to describe uncertainty in the context of the sets of uncertainty factors that would affect judgments about and choices among alternative policies, following the identify options, assess risks, evaluate trade-offs loop in Figure 2-2. The literature offers several names for such approaches, including 'context-first' (Ranger et al., 2010), 'decision scaling' (Brown et al., 2011), 'assess risk of policy' (Lempert et al., 2004; UNDP, 2005; Carter et al., 2007; Dessai and Hulme, 2007) that characterize those uncertain states of the world that would cause a current or proposed policy to fail to meet its goals or the to illuminate the trade-offs among particular policy choices. For instance, Kirshen et al. (2008) provided decision makers in New York City plots that showed how the frequency of large-scale flooding would increase along the city's coastline, without changes to the current infrastructure, as a function of various assumptions about sea level rise. The IPCC's *Reasons for Concern* approach (Smith et al., 2009) aims to summarize the deleterious impacts implied by various greenhouse gas emissions trajectories. In engaging with decision-makers, this assess-risk-of-

policy approach often requires that information providers work closely with decision makers to understand their plans and goals, before customizing the uncertainty description to focus on those key factors. This approach can be very effective at communicating risk and uncertainty, but often needs to be individually customized for each decision context (Lempert and Kalra, 2011; Lempert, 2012) and requires the producers and users to collaborate within a single process.

Within these processes, a number of approaches exist for dealing with uncertainty in CCIAV decisions. Traditional probabilistic approaches treat uncertainty with a single, well-characterized (joint) probability density function over future states of the world. Such approaches have been used in a wide variety of adaptation studies (Hobbs et al., 1997; Chao et al., 1999; Venkatesh and Hobbs, 1999), often within a predict-then-act process, and can prove most useful when the uncertainty is relatively well-characterized or when decision makers seek an authoritative expert judgment to inform their choices.

A variety of axiomatic approaches also exist (Smithson, 1989), such as belief functions (Shafer, 1976), imprecise probabilities (Walley, 1991), certainty factors (Clancey and Shortliffe, 1984), and fuzzy logic (Zadeh, 1983; Prato, 2009, 2011), which aim to provide formalized descriptions of multiple levels of uncertainty, generally combining likelihood with some additional measure of confidence (Climate Change Science Program, 2009). While some examples exist (e.g., Bass et al., 1997; Prato, 2009, 2011), such approaches have not been widely used for CCIAV decisions.

Sets of alternative representations can also be used to characterize uncertainty. Such approaches, often but not always used within a context-first process, aim both to decrease tendencies towards overconfidence as well as facilitate engagement with the analysis among parties with differing expectations and values. These set-based approaches can focus on non-probabilistically weighted collections of future states of the world or can retain a probabilistic formulation by considering a range of probability values or sets of plausible probability density functions, for instance as suggested in the IPCC uncertainty guidance (Mastrandrea et al., 2010). Examples include InfoGap, which has been used to inform CCIAV decisions in water management (Ben-Haim, 2001; Korteling et al., 2013); RDM (robust decision making), which has been used for water management and flood risk management planning (Lempert et al., 2003; Lempert and Groves, 2010; Lempert and Kalra, 2011; Matrosov et al., 2013); and robust control optimization and control theory (Hansen and Sargent, 2008). Note that the climate modelling community has also begun to adopt set-based characterizations of uncertainty (see Parker, 2006).

Scenarios

Scenarios are cognitive tools central to scoping and assessing risk, and in managing risk as adaptation planning *[very high confidence]*. A scenario is not a prediction of what the future will be but rather a description of how the future might unfold. A scenario includes an interpretation of the present, a vision of the future and an internally consistent account of the path from the present to the future (Jäger et al., 2008). Scenario use has expanded significantly as CCIAV research has become more integrated with mainstream activities. Their application has extended beyond climate as noted in the past two assessment reports (Carter et al., 2001; Carter et al., 2007). Climate change has also become a core feature of many scenarios used in regional and global assessments of environmental and socio-economic change (Carpenter et al., 2005; Raskin et al., 2005). Scenarios can be used at a number of stages within the assessment process or to underpin an entire assessment. They serve a variety of purposes, including informing decisions under uncertainty, scoping and exploring poorly understood issues, and integrating knowledge from diverse domains (Parson et al., 2006).

Existing scenario typologies tend to reflect the state of play at the time they are assembled, become outdated as the field evolves and often fail to capture the full range of contemporary scenario development (van Notten, 2006). They seem to be regarded as products of research, rather than as tools designed to function in particular sorts of inquiries (Wilkinson and Eidinow, 2008). Recently published typologies include descriptive (van Notten, 2006), philosophical underpinning (Börjeson et al., 2006) and decision-type (Wilkinson and Eidinow, 2008). These typologies can be grouped according to their function in decision-making. The major groupings are problem-based, solution- or actor-based and reflexive scenarios (Wilkinson and Eidinow, 2008). Exploratory scenarios that explore

value-neutral 'what will happen if' questions and normative scenarios that represent explicit values in a forecasting or back-casting mode are also important pairings (Carter et al., 2007). Problem-based scenarios are developed using deductive and inductive methods whereas actor-based scenarios are normative, so map well onto exploratory and normative scenarios.

Reflexive scenarios are designed to work with wicked problems (Wilkinson and Eidinow, 2008). Problem (exploratory) and solution- or actor-based (normative) scenarios are combined to assess problems, implement decisions and apply ongoing learning in action-based research. Such scenarios require an institutional host, are linked to data measuring progress towards outcomes and periodically updated within an iterative assessment framework to revise decisions (Jones, 2012). Several generations of scenarios produced by IPCC assessments, national climate scenarios in the UK and Australia indicate this capacity may be developing (CSIRO and BoM, 2007; Gawith et al., 2009; Moss et al., 2010) but would require parallel development in a wider set of variables relevant to adaptation and a more institutionalised approach to decision-making support. The new scenario matrix being developed for climate change (Kriegler et al., 2010; Moss et al., 2010) is one vehicle where this may happen.

Linking these typologies with research methods, the major determinants of scenarios can be described as problem–actor, exploratory–normative, top-down–bottom-up (in terms of scale) and forward-looking–back-casting (or prescriptive-diagnostic in terms of time). In methodological terms this sets up a process-goal construct. Forward casting normative scenarios concentrate on the initial state and process, for example a set of specific policies, whereas back-casting will define a normative state in the future; e.g., sustainability, then diagnose how to achieve that state over time given specific starting conditions and a set of key drivers. Reflexive scenarios will combine these approaches.

Scenarios have a somewhat uncomfortable place within the standard research methods applied to assess CCIAV. As outlined in the earlier section on uncertainty, problem uncertainty can range from quantified distributions of variables and outcomes known with high confidence to those that can at best be said to be 'not implausible' (Strzepek et al., 2001; Malone and Yohe, 2002) that are linked to complex situations with deep uncertainty.

There is a tension between the development of climate forecasting as pursued by the modelling community who aim to improve future predictions and scenario development required by the CCIAV community, who require tools for decision support. In terms of calculating event risk, scientific prediction is limited to what is represented in a model, so while its theoretical application may be sound, in a system of multiple drivers and feedbacks, the model itself may be incomplete. Scenarios can fill that gap. For example, Carter et al. (2007) emphasize that climate scenarios are usually purpose-built for specific impact assessments, often modifying climate model output, but rarely use model output directly. Climate may also be only part of the total uncertainty if risk is being assessed from the interaction between climate impacts and social vulnerability.

On the solution side, representing hard-to-define goals is also a difficult issue for prediction. For example, both sustainability and 'dangerous climate change' are both difficult to define due to differing social and cultural constructions of what they may mean. This uncertainty is reflected in the expert literature (Harding, 2006). Uncertain predictions of uncertain goals invite controversy. Given that exploratory scenarios have the capacity to survey a range of plausible pathways and goals in such cases, a participatory process is likely to achieve broader agreement than expert judgment can by itself.

The inability to ascribe likelihood to a single scenario can be overcome by using scenario ensembles, allowing storylines to be compared and contrasted. Quantitative estimates such as warming or population growth can be assessed according to likelihood of exceedance because cumulative statistical functions are more robust to uncertainty than probability distribution functions. Likelihood can be addressed in a Bayesian manner, where participants use a scenario process to update their priors, but in a richer manner than can be achieved with straightforward prediction. For example, a stakeholder's prior model may be completely altered, they may step away from a focusing on the most likely outcome to survey the spectrum of potential likelihood consequence, or they may completely reframe the way they see the issue. The ability to do this collectively also fosters social learning, potentially building a community of practice (Wenger, 2000; Pahl-Wostl, 2002).

By separating risks into tame and wicked problem risks, the need for scenarios with the decision-making process can be better identified *[moderate confidence]*. For tame risks, if probabilities cannot be easily calculated then scenarios can be used to explore the problem and illustrate alternative solutions for evaluation. Wicked problems will probably need to be thoroughly scoped to select the most suitable decision-making process. They may require separate applications of problem and solution-based scenarios or the development of reflexive scenarios. Even if conditional predictions can be used to illustrate climate futures, scenarios may be needed to explore the solutions space involving strategic actions, options planning and governance using both process and goal-oriented methods.

2.2.1.2. Evaluating Trade-Offs and Multi-Metric Valuation

Effective CCIAV decision-making often requires making trade-offs among competing objectives and values. The methods and tools that exist to help evaluate such trade-offs employ a range of alternative decision criteria. The appropriate criteria for any given case depends on decision makers' the goals, the data available, and the types of uncertainties involved. Implicitly and explicitly, these decision criteria are used throughout the discussions of adaptation options, planning, and economics in Chapters 14 through 17 and WG III Chapter 2.

The decision theoretic literature divides criteria relevant to CCIAV decision making into two broad categories: outcomes-based, which compare alternative actions according to the consequences expected to result from them, and process -based, which compare alternative actions according to the process by which any decision is arrived at and, in particular, the extent to which various individuals consent to the risks, costs, and obligations being imposed upon them (Morgan et al., 1990). In general, CCIAV decisions can be judged by both types of criteria.

Process-based criteria focus on the credibility and legitimacy of a decision process. Institutional (Section 2.2.2) and cultural (Section 2.2.3) contexts will strongly influence the appropriateness and importance of such criteria. For some participants and in some situations, process criteria may prove decisive in any judgments about the decision irrespective of the outcome (Dietz and Stern, 2008; Sen, 2009). For instance, many environmental laws require advanced notice and periods of public comment before the government issues any regulations. Legal systems with water rights often give allocation decisions over certain water resources to individuals who can then choose, or not, to sell them to others during periods of drought. Participants may regard any decision that fails to respect these rights as illegitimate. One fundamental purpose of democratic deliberation and decision-making is to confer legitimacy on decisions (Sen, 2009). Process-based criteria can also depend on judgments about uncertainty. For instance, the precautionary principle contains an element of process-based criteria, placing the burden of proof on those introducing new impacts on the environment to prove that they are not harmful. Some utilitarian-based ethical frameworks distrust the ability to compare in any meaningful way social outcomes that make one person better off and another worse off, and thus seek to minimize the scope of decision processes that adjudicate broad social outcomes and seek to expand the scope of decision processes, often market-based, in which individuals only engage in transactions that transfer costs or risks with their explicit consent.

Outcomes-based criteria focus on the extent to which the consequences that flow from a decision met decision makers' goals. Most generally, these criteria fall within the domain of *multi-attribute decision theory* (Keeney and Raiffa, 1993), which provides a framework for balancing among multiple, potentially competing objectives (this branch of decision analysis is also known as multi-criteria decision analysis; for a CCIAV example see Korteling et al. (2013)). In some cases decision support uses decision criteria that recommend a single best decision, often by aggregating all the relevant objectives into a single metric. In other cases, decision support uses criteria that summarize trade-offs for decision makers.

Among criteria that recommend a single best decision, *optimality* provides the best possible outcomes-based choice in those situations where it is possible and appropriate to aggregate the relevant objectives, often expressed as monetary cost. *Cost effectiveness* criteria often prove useful in situations where decision makers can quantify the costs but not the benefits of alternative actions. For instance a water management agency might determine it necessary to be able to maintain a reliable supply of water in the face of the largest drought ever observed in their region, and then choose to invest in the least expensive reservoir able to meet that criteria. *Bounded cost* criteria often prove useful in situations where decision makers have fixed resources to address a problem. For instance, a

city might have a fixed budget to address adaptation to climate change and may wish to allocate those resources in such a way as to reduce risks as much as possible.

Such criteria can also help to summarize trade-offs among multiple objectives. For instance, one could use a cost effectiveness criterion to compare the cost of achieving alternative objectives, such as different levels of reliability for a water agency. More generally, *modern portfolio theory* (Crowe and Parker, 2008) provides what are called Pareto optimal surfaces that balance among multiple objectives. Each point on the surface represents the combination of objectives achieved by some decision, such that it is impossible to perform better for any one objective without performing worse on some other.

The multiple levels of uncertainty addressed in Section 2.2.1.1 can affect the appropriateness of alternative decision criteria. While some criteria can be applied broadly, some are only applicable with some types of uncertainty characterizations (Dessai and Sluijs, 2007). *Optimality* can provide the best possible outcomes-based choice when uncertainties are well-characterized. Criteria also exist to recommend a single best decision in cases where uncertainties are deep. For instance, the *maxi-min* criterion suggests choosing the decision with the best worst-case outcome and the *mini-max regret* criterion (Savage, 1951) suggests choosing the decision with the smallest deviation from optimality in any state of the world. Proposals for 'no regrets' adaptation decisions (Callaway and Hellmuth, 2007; Heltberg et al., 2009) employ such criteria. Hybrid criteria that balance between optimal and worst case performance have also been used to support climate related decisions (Hurwicz, 1951; Aaheim and Bretteville, 2001; Froyn, 2005).

In some cases, however, higher levels of uncertainty can also motivate the use of decision criteria that summarize trade-offs for decision makers. For instance, some CCIAV literature has used robustness, a satisficing criteria (Rosenhead, 1989) that seek decisions that will perform well over a wide range of plausible climate futures, socio-economic trends, and other factors (Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Robustness criteria can often illuminate trade-offs that help decision makers achieve consensus on actions event when they do not agree on expectations about the future. The literature offers differing statements about the relationship between robustness and resilience (Folke, 2006; Gallopín, 2006), but resilience, described in detail in Chapter 20, tends to describe a property of systems, which might be affected by decision makers' choices, while robustness is a property (or not) of the choices made by those decision makers. Methods also exist to summarize trade-offs for decision makers for multiple objectives and higher levels of uncertainty, for instance by suggesting decisions that are robust over many futures and objectives (Kasprzyk et al., 2013).

2.2.1.3. Learning, Review, Evaluation, and Reflexiveness

Learning is a crucial aspect of CCIAV decision-making because climate change is sure to surprise us, both in its impacts and in the technological and behavioural changes that will affect society's ability to respond (National Research Council, 2009a). Much adaptation literature, including the iterative risk management framework (Figure 2-2), thus stresses the importance of decisions, systems, and processes that effectively respond over time to new information. Such new information includes observations of events that have occurred and anticipation of events that may occur in the future. For instance, the resilience literature provides frameworks for identifying systems with the ability to respond successfully to shocks. The climate adaptation literature distinguishes between *coping* and *adapting* (IPCC, 2012), and between *planned* and *unplanned* adaptation, to explore the benefits of appropriate responding to anticipated future events. Chapter 18 discusses the monitoring of impacts, necessary to any successful response. Learning processes are central to the discussions in Chapters 14 through 17 and in Chapter 20.

The concepts of adaptive management and adaptive decision-making, important themes in the CCIAV literature, can help decision makers incorporate learning into their plans. Adaptive management has a specific meaning in the literature, referring to situations in which the choice of policy is strongly influenced by a requirement to generate reliable new information (Holling, 1978, 1996), but the term is often used more generally to refer to policies that are designed to respond to new information. The former, sometimes called active adaptive management, might involve forest managers who purposely pursue alternative management practices on similar plots of land to gather scientific

data on the most effective practices. The latter, sometimes called passive adaptive management, might involve a water management agency that pursues a portfolio of supply investments, largely to manage risk, but also intending to shift investments in the future depending on which prove most successful. In both forms, adaptive management focuses on process and continuous learning (trial and error, small step→evaluate→adjust) (Dessai and Sluijs, 2007).

Methods and tools exist to help decision makers evaluate alternative adaptive strategies. These approaches are often used to represent the benefits and costs of learning in studies and simulation models that support climate-related decisions. The sequential decision approach, commonly used in the climate policy literature, represents policies as a sequence of choices over time, made with different amounts of information (Nordhaus, 1994). The real options approach draws from the finance literature to represent a near-term choice as creating the ability to make specific future choices under certain conditions. Real options approaches have recently been used in some adaptation studies (Hertzler, 2007) as well as those addressing greenhouse gas emissions reductions (Blyth et al., 2007) and investments in emissions reducing energy technologies (Mahnovski, 2007). Control theory provides another such representation (Funke and Paetz, 2011). Each approach can be used with many uncertainty representations and decision criteria.

Successful adaptive management and decision-making requires the inherently complex challenges of monitoring and evaluation (Governance and Social Development Resource Center, 2001). Decision makers concerned with monitoring and evaluation of adaptation policies, programs, and projects may determine what attributes to measure, for instance adaptive capacity, resilience, reduction of exposure, or vulnerability. Other dimensions include temporal scales, structural and non-structural measures (e.g., information sharing-flood forecasting and warning and behavioral changes) (Governance and Social Development Resource Center, 2001; Hedger et al., 2008). In some cases, it may also be useful to define an adaptation baseline(s) in order to evaluate the success of an implemented policy (Ebi et al., 2005; Vidhi and Sharma, 2010).

For example, Bangladesh has proposed a monitoring strategy for their already adopted national adaptation strategy and action plan. The action plan is comprised of six pillars – food security, social protection and health; comprehensive disaster management; infrastructure; research and knowledge management; mitigation and low carbon management; and capacity building and institutional strengthening (Government of Bangladesh, 2009). The plan calls for monitoring and evaluation of interventions for three purposes: their ability to reduce climate change vulnerabilities of human populations and natural and economic systems; their efficiency, flexibility, equity, results, cost-effectiveness and sustainability of the interventions (Hedger et al., 2008; Vidhi and Sharma, 2010); and their ability to avoid maladaptation (Mirza, 2009).

The decision support systems themselves can usefully be designed as learning processes. One useful approach, *deliberation* with analysis, provides an iterative process that begins with the many participants to a decision working together to define its objectives and other parameters, working with experts to generate and interpret decision-relevant information, and then revisiting the objectives and choices based on that information (Figure 2-4). Deliberation with analysis often proves most useful in situations with diverse participants to a decision in a changing environment whose goals emerge from deliberation and may change over time (National Research Council, 2009a; see Box 2-2 on the Louisiana Coastal Master Plan).

[INSERT FIGURE 2-4 HERE
Figure 2-4: Deliberation with analysis decision support learning process.]

Adaptive management and decisions can provide a means to develop strategies robust over a wide range of uncertainties, and has been increasingly pursued in many applications (Williams et al., 2009). However, adaptive management can be difficult to implement (National Research Council, 2009a), in large part because, without appropriate institutions, such strategies can be difficult to maintain. Monitoring and evaluation can prove difficult and costly, decision makers can be reluctant to gather data they may show their policies are not succeeding, and their organizations may not be sufficiently flexible to respond appropriately to new information (Lee 1993). In some cases decision makers may distrust the willingness or ability of their successors to respond to new information and will find it advantageous to enact policies that are difficult to change in the future.

The literature explores the relationships between learning and organizational change that can affect the ability of adaptive strategies to meet their goals in the face of uncertainty. The learning loop framework (Kolb and Fry., 1975; Argyris and Schön, 1978; Keen et al., 2005) divides learning processes into three categories, depending on the degree to which learning promotes transformational change in an organization's strategies. Single-loop learning processes focus on improving an organization's plans (Pelling et al., 2008) by adjusting policies based on the difference between what is expected and what is observed. Double-loop learning, in contrast, uses new information to question basis assumptions and reevaluate current knowledge, objectives, and strategies. Adaptive management, deliberation with analysis, and scenario practice are all processes that aim to routinely facilitate such double-loop learning by using data both to take corrective action and to change the frames through which issues are conceptualized. In triple-loop learning (Argyris and Schön, 1978; Peschl, 2007; Hargrove, 2008), decision makers may begin to question deep underlying principles (Pelling et al., 2008), for instance, considering how institutional and other power relationships determine perceptions of what is to be done and how (Flood and Romm, 1996). In response, they might seek to address how social structures, cultural mores, and other structures might be changed or transformed. The distinction between single-, double-, and triple-loop learning thus helps highlight the types of adjustments decision-makers can consider in the face of potentially significant, abrupt and surprising changes that may result from the interaction of climate change and socio-economic trends.

2.2.2. Institutional Context

Virtually all CCIAV decisions will be made by or influenced by institutions. The institutional context will thus prove an important influence on these decisions and on the way decision support is organized.

2.2.2.1. Institutions for Capacity Building

Institutions are imperative for effective management of climate change risks through proper governance. Institutions are defined as "…systems of rules, decision-making procedures, and programs that give rise to social practices, assign roles to the participants in these practices, and guide interactions among the occupants of the relevant roles" (IDGEC Scientific Planning Committee, 1999). Each institution has a set of objectives and goals that may be explicit or implicit and as such, each displays unique characteristics. The strength and nature of their role in maintaining a cohesive society enables societies to adapt to crises (O'Riordan and Jordan, 1999)**.** Institutions can facilitate environmental protection on one hand but on the other can also accelerate resource depletion by designing and implementing counter-productive policies (Scharpf, 1997). Institutions can constrain and shape human interaction through direct control, through incentives, and through processes of socialization (WGIII; SRREN). The rules and roles of institutions for whatever reason(s) they have been created can be of many forms: formal and informal, visible and latent, and conscious and unconscious (Arts et al., 2006). Governments create formal institutions that play an important role in vulnerability reduction and adaptation (Gupta et al., 2008). Agarwal et al. (2008) analyzed the roles of local institutions in adaptation and categorized them into local public, civil society and private institutions. As adaptation is generally a local issue, local institutions play important roles in the process by interacting with national and regional institutions.

Smit et al. (2001) identified institutions as one of the key determinants of adaptive capacity. Countries with strong institutions are generally assumed to have a greater capacity to adapt to current hazards and disasters as well to the future. However, this is not necessarily true in all cases. Hurricane Katrina of 2005 in the USA and the European heat waves of 2003 demonstrate that strong institutions and other determinants of adaptive capacity do not necessarily reduce vulnerability if not translated to actions (IPCC, 2007)(also see in section 2.3.2.2). Generally for economic and technological reasons, most of developing countries have weaker institutions that are less capable of managing hazards and disasters of catastrophic nature. For example, Lateef (2009) conclude that institutional weaknesses in healthcare and disaster preparedness led to high casualties from the cyclone Nargis in Myanmar in 2008.

Uniform presence of institutions can reduce vulnerability and contribute to increase adaptive capacity. Berman et al. (2012) suggest that institutions play a key role in mediating the transformation of coping capacity into adaptive

capacity and in linking short and long-term responses to climate change. Institutions that can appropriately respond to climate challenges are unevenly distributed especially within marginalized regions or indigenous territories. Examples from Latin American demonstrates that institutional limitations can prevent the effective participation of indigenous people in climate change adaptation initiatives (Kronik and Verner, 2010).

Climate change is a development issue and the risks from climate change could significantly impact sustainable development in developing countries. Mirza (2003) argued that vulnerability to extreme weather events, disaster management and adaptation must be part of the long-term sustainable development planning in developing countries. This will require development assistance to explicitly consider climate change risks, and to include capacity-building to respond to climate change as a part of investments in recovery and infrastructure development. Multilateral institutions are responding to these challenges. For example, the World Bank supports both reactive and pro-active types of projects on adaptation (Agarwal et al., 2008).

Aid is becoming more focused on adaptation to climate change, disaster risk reduction and adaptation are merging at the policy to program levels and traditional activist and advocacy organizations are becoming more professional and being involved in program delivery. Bartley (2007) describes the latter as a form of channeling where foundation patronage and organizational field building is leading to social movement organizations becoming involved in mainstream project delivery. This model fits the growth of adaptation where aid funders such as USAid and foundations such as the Rockefeller and Gates Foundations are providing complementary funding that is fuelling program delivery involving environmental and development NGOs with local stakeholders (Ziervogel and Zermoglio, 2009; Kolk and Pinkse, 2010; Worthington and Pipa, 2010).

Understanding collective institutional or organizational frames offers a way to overcome barriers to adaptation when competing collective frames such as economy versus environment are preventing the integration of both into policy and action (e.g., Hoffman and Ventresca, 1999). Frame structure, content, dynamics and diffusion can be understood in order to encourage social movements to action around an issue, through diagnosis, prognosis and motivation (Benford and Snow, 2000). Discursive frame analysis that understands how various issues are described, the actors involved and their methods of organization. Brulle (2010) discourages targeted public campaigns intending to increase awareness and thus action that are based on cognitively and psychologically-designed appeals to the individual for a more participatory approach based on civic engagement using a process called Analytic Deliberation.

2.2.2.2. Governance, Legal Dimensions, and Decision Implementation

Governance is often visualized as a rigid, centralized, unitary, top-down process of rules and policy development in the public interest that have to be implemented at local level (Commission on Global Governance, 1995). Krahmann (2003) argues that governance is considered as a flexible, diffuse, bottom-up and top-down process that interact between different tiers of government and with a range of social actors. Governance and good governance are often seen as key institutional settings for addressing problems (Botchway, 2001). Climate change governance requires action for both adaptation and mitigation. IPCC (2007) stated that many early impacts of climate change could be effectively addressed through adaptation but the options for successful adaptation diminish and the associated costs increase with increasing climate change. However, adaptation alone is not expected to cope with all the projected effects of climate change, especially not over the long term as most impacts increase in magnitude (IPCC, 2007). Governance of adaptation requires knowledge of anticipated regional and local impacts of climate change (Meadowcroft, 2009).

Climate change and the associated risks have national and international legal dimensions. There are many *national level* legal implications of climate change. Considering Bangladesh as a case study, Freestone et al. (1996) identified that nationally climate change and sea level rise would affect property rights and land tenure, population displacement, rehabilitation and resettlement, and institutional frameworks involving with these issues. The *international legal aspects* of climate change impacts and risks would come from a variety of angles. Sea level rise could alter the *maritime boundaries* of many nations that may lead to new claims by the conflicting nations. The open waterways for shipping is very *likely* to change in specific, measurable ways in the next several decades

Reductions in sea ice in the Arctic may allow new trade passages such as the North West Passage to be established (Chapter 6). Climate change could also lead to access to resources that were previously technically inaccessible and that may result in new territorial claims. Runoff changes in the international rivers due to reduced seasonal precipitation could result in new *water conflicts* and *energy utilization* among the co-basin countries and can also pose challenges to the already signed sharing agreements (Kim, 2010). Additional *food insecurity* due to climate change will pose a moral challenge and human rights question regarding food supply from the developed countries to affected regions. Many national and international legal institutions and instruments need to be updated to face climate related challenges and decision implementation.

2.2.3. Social Context

Decision support for CCIAV must recognize that people and culture with its diverse values, language uses, ethics and human psychological dimensions play a crucial role in the way that people use and process information and take decisions (Kahan and Braman, 2006; Leiserowitz, 2006).

2.2.3.1. Value Setting

The majority of climate change research conceptualizes values as monetary worth, relative worth, or fair return on exchanges, drawing primarily on welfare economics and using cost-benefit analysis or contingent valuation to estimate losses (Watkiss, 2011). These values reflect a neoclassic economic framing of the issue. Increasingly, however, a number of authors have argued that a broader conceptualization of values is needed to understand and respond to climate change (Adger et al., 2009; O'Brien, 2009; O'Brien and Wolf, 2010). Chapter 17 investigates the use of tangible and intangibles in assessing the economics of adaptation, but here we take a broader look at how values influence decision-making.

In this broader conceptualization, values are understood as the subjective, qualitative and intangible dimensions of climate change and its impacts that are of importance to individuals and cultures (O'Brien and Wolf, 2010). Such values may concern how climate change affects, for example, place identity, land-based or traditional practices important for cultures, and the symbolic meanings of places and practices, in particular where irreversible losses may occur. Such values shape how the effects of climate change are perceived and how responses, including adaptation decisions, are addressed.

In the context of dangerous climate change, it has been acknowledged that judgment and "values matter for converting science into policy" (Oppenheimer, 2005, p. 1401). Others argue that the difficulty in compensating for irreversible losses due to incommensurable values points to a need for other principles, such as the precautionary approach, to be utilised in global climate policy (Adger et al., 2011). O'Brien and Wolf (2010) suggest that people's value orientations be allowed to determine what is perceived to be worth preserving and maintaining through adaptation (and indeed mitigation) decision making. Despite a growing recognition that values matter, however, there is limited research that explicitly considers the role that such values play in shaping adaptation decisions.

The importance of values in decision making related to climate change are operating at two levels:

1) Larger socially shared values of a given culture and of groups and individuals within that culture
2) Values related to the work, including decision making, in modern organizations and in management.

The first issue is mainly studied by anthropologists, cross-cultural and environmental psychologists, revealing an important diversity of values across cultures that influence individual, local, national, even international decision-making. Values, as abstract entities, guide decision-making processes and are realized in real acts. The anthropological literature shows the importance of religious, sacred values related to climate (Goloubinoff et al., 1998; Katz et al., 2002; Lammel et al., 2008). Such values can inform the perception of climate change, as well as the actions to protect against its consequences (Crate and Nuttal, 2009).

The values of a given society are fundamental to the development of attitudes, cognition, emotions and behaviors. Kluckhohn and Strodtbeck (1961) identified five basic, relatively stable value orientations (Values Orientation Theory) that allow societies to find value-based solutions to universally important questions. Three of the five value orientations influence climate change related decisions: peoples' relations with time, nature and each other:

- For temporal values, the main cultural differences concern time orientation (past/present/future)
- For the relationship with nature, cultural differences involve mastery, harmony, submission
- For the relationship with each other, the three culturally different value orientations are: hierarchical (lineal); egalitarian (collateral) and individualistic.

Kluckhohn and Strodtbeck (1961) theory influenced a great number of cross-cultural and environmental psychological studies seeking 'universal' dimensions of values and their culturally different manifestations (e.g., Hofstede, 1980; Schwartz, 1992; Hofstede and Hofstede, 2001; Rokeach, 2008).

Environmental decision making is highly influenced by culturally elaborated values. Schultz et al. (2004) link values, attitudes, world views and behaviours to the environment. They differentiated three sets of values, described previously by Stern et al. (1995):

1) *Egoistic values* focused on values and goals oriented toward the interest of the self (me, my future, my wealth, my health)
2) *Altruistic values* focus on others (future generations, humanity, people of the community, children)
3) *Biospheric values* focus on the wellbeing of living things (plants, animals, marine life, birds).

Schultz et al. (2004) tested whether differences in a person's information processing could be correlated with their connection to nature. They concluded that a weak connection with nature is associated with local information processing; conversely, a greater connection is associated with more comprehensive information processing. Many studies have added new perspectives (e.g., Milfont and Gouveia, 2006; Soyez et al., 2009) showing that cultural values can substantially influence the decision-making processes. Values are also related to 'environmental concerns' (Stern and Dietz, 1994; Xiao and Dunlap, 2007) influencing public behaviour toward policies. Schaffrin (2011) insists that geographical aspects, vulnerability and benefits from policies are important in value orientation and can influence the vision global/local and short term/long term dimensions of climate change (e.g., (De Groot and Steg, 2007, 2008; Shwom et al., 2008; Milfont et al., 2010). Pelling et al. (2008) found that accounting for values within officially and unofficially-sanctioned relationships could enhance social learning and therefore adaptive capacity. Nyong et al. (2007) found that the moral economy in indigenous African communities provided direction for implementing both adaptation and mitigation actions.

The cultural theory of risk perception (Douglas and Wildavsky, 1982) has also been used to successfully group beliefs on contentious scientific issues such as climate change using the structural settings *hierarchical* and *egalitarian* with the value settings *individualist* and *communitarian* (Kahan et al., 2007; Kahan, 2008). It has been proposed that such knowledge could contribute to various policies on adaptation by tailoring the framing of those policies according to the belief structures inherent within cultural theory (Adger et al., 2009; O'Brien and Wolf, 2010).

National values also influence local organizational values. Hofstede (1980); Hofstede and Hofstede (2001) using a large database, collected in subsidiaries of the multinational corporation IBM, identified firstly in 40 and later in 76 countries (Hofstede et al., 2010), five value dimensions with significant cross-national differences: power distance, individualism/collectivism, uncertainty avoidance, masculinity/femininity and long/short term orientation.

While a substantive gap exists in research that can apply knowledge of personal and cultural values to decision-making on climate change, this area is receiving a good deal of attention (Nilsson et al., 2004; Leiserowitz, 2006; Lorenzoni et al., 2007; De Groot et al., 2010). The above studies on values can provide important theoretical and methodological tools for further research and its integration into decision making practices. Such research could assist in building legitimate, transparent and inclusive responses including policy on climate change [moderate confidence].

2.2.3.2. Cultural Determinants and Psychology

At the individual level, decision-making is a multi-directional and non-linear cognitive activity. Responses to new information can modify previous decisions, even producing contradictory results. Decision-making in climate change problems cannot be described as rational and can negatively affect environmental behaviour (Grothmann and Patt, 2005; Marx et al., 2007). Many strategies are used by individuals in making adaptation decisions (Fischer and Glenk 2011) suggesting that a uniform approach to problem solving is unlikely to succeed.

Ignatow (2006) distinguishes between two cultural models: the 'spiritual' and the 'ecological' that have different social bases. Western education generally involves the second but not the first. In the spiritual model, nature is sacred, has its own rights and should be kept separate from human society. It is threatened by science and technology and has to be respected. The ecological model represents nature as an ecosystem physically integrated into human society (Bocking, 1994). There is no inherent conflict between the society and nature, thus science and technology can be used to integrate modern society with the natural environment (Oates, 1989).

The perception and representation of nature and the environment are influenced by the dominant modes of thought in a society. Cultural psychology distinguishes between two main systems of thought: holistic and analytical thinking (Lammel and Kozakai, 2005; Lammel et al., 2011). Holistic thinking characteristic of collectivist societies consider that social obligations are reciprocal and individuals take part in a community with strong ties (Peng and Nisbett, 1999; Nisbett et al., 2001), such as in a gift economy. Such holistic thinking is built primarily on the knowledge gained through experience and not through abstract logic. It is dialectical and accepts contradictions and multiple perspectives, trying to find a middle stance between opposing propositions. Holistic thinking is associative and its computations reflect similarity and contiguity.

In more individualistic societies, the analytical model is central. Individual interests take precedence over societal interests; the self is independent and communication comes from separate fields: benchmarks are not common. The object is isolated from its context; the focus is on understanding the characteristics of the object to determine its category membership, and explain and predict events based on its intrinsic rules. Inferences are derived from contextualizing the content structure, using formal logic and avoiding contradiction. Analytical thinking circumscribes symbolic representation systems; instead its formalization is built on structures of rules. Several studies demonstrate the influence of this way of thinking on complex problem-solving (e.g., Badke-Schaub and Strohschneider, 1998; Strohschneider and Güss, 1999; Güss et al., 2010).

An increasingly extensive literature highlights the importance of taking into account cultural/local knowledge, traditional ways of thinking and traditional methods of decision-making when assessing CCIAV (Vedwan, 2006; Nyong et al., 2007; Dube and Sekhwela, 2008).

Psychological factors

The psychological literature on decision in context can help to understand how to make better decisions. Several theories, such as the multi-attribute utility theory (Keeney, 1992), prospect theory (Kahneman and Tversky, 1979; Hardman, 2009), and the cumulative prospect theory relate to decision making under risk or uncertainty (Tversky and Kahneman, 1992). Recent cognitive approaches, such as the one-reason decision process (e.g. (Gigerenzer and Goldstein, 1996) or the decision by sampling theory (Stewart et al., 2006; Stewart and Simpson, 2008) integrate even more psychological factors.

Personal dilemmas are frequently related to utility and probability (short/long term) (e.g., Hoch and Loewenstein, 1991). Social dilemmas are very important because individual utility maximization can cause collective loss ('commons problem') (Hardin, 1968). Decision-making can also be realized without thinking. The dual process theory of thought states that human being possess 'two minds'. System 2 is rational (trade-offs between utility and probability) meanwhile the System 1 is intuitive, an unconscious kind of thought (Myers, 2004; Stanovich, 2005), leading to frequently observed behavioral inconsistency. In terms of cognitive economy, decision making without

thinking or by 'feelings' are automatic, unconscious, fast and effortless and widely used (Slovic et al., 2002; Evans, 2008).

Psychological factors important for decision-making on climate change include: perception, representation, knowledge acquisition, behavior, emotions and understanding of risk (Oskamp and Schultz, 2006; Gifford, 2008; Kazdin, 2009; Reser et al., 2011; Swim et al., 2011). Investigations of public perception and climate change representation (e.g., Böhm and Pfister, 2000; Lorenzoni et al., 2006; Sterman and Sweeney, 2007) suggest that certain perceived characteristics of climate change may lead individuals to underestimate the magnitude of risk (Böhm and Pfister, 2000; Sundblad et al., 2009). Different explanations include (Leiserowitz, 2006): (1) Optimism, downsizing personal risks; (2) The perceived signs of climate change seem to be "natural"; (3) Perceived as normal variations in weather; (4) Natural variation in the world's climate is a low risk; (5) People probably do not have necessary emotional or cognitive capacities to make an adequate risk evaluation. These findings show the importance of experiential factors in understanding phenomena and the strong influence of experiential decision making as contrasted with analytic decision making.

Psychological obstacles in processing climate change information include psychological distances that have four theorized dimensions: temporal, social, and geographical distance, and uncertainty (Spence et al., 2012). Attitudes and behaviors relevant to climate change engagement, include place attachment (Scannell and Gifford, 2013), political affiliation (Davidson and Haan, 2011), and perceived costs and benefit (Tobler et al., 2012).

The relationship between cognition and behavior influences people's adaptive actions, especially to perceived risk and the effectiveness of action. Grothmann and Patt (2005) apply a socio-cognitive model of proactive private adaptation to climate change impacts that predicts, for instance, if a high risk is combined with low capacities response is fatalism, denial and wishful thinking. Emotional factors also play also an important role in climate change perception, attitudes, decision making and actions (Meijnders et al., 2002; Leiserowitz, 2006; Klöckner and Blöbaum, 2010; Roeser, 2012) and even shape organizational decision making (Wright and Nyberg, 2012).

Knowledge about climate change is necessary to increase overall concern and greater perceived efficacy and responsibility (Milfont, 2012). However studies in education (Rajeev Gowda et al., 1997; Boyes et al., 1999; Andersson and Wallin, 2000) show the difficulties in understanding the scientific process of global climate change. Shepardson et al. (2012) insist that a systemic vision of climate is needed for such understanding. Even highly educated adults can have a very elementary cognitive representation of climate change, creating cognitive vulnerability (Lammel et al., 2012). In the USA, limited understanding has led to "wait-and-see policies" and to the absence of effective decision making on adaptation (Sterman and Sweeney, 2007; Dutt and Gonzalez, 2012). Even policy makers have cognitive difficulties in understanding climate change, for instance, in Sweden, their knowledge is less important than journalist's knowledge (Sundblad et al., 2009).

Sterman and Sweeney (2007) propose to communicate climate change issues through clear analogies and metaphors. Other form of intervention to help the development of climate change knowledge and concern, without the experiential factor, can be the simulations by stirring artistic approaches (films, music, paintings) and the activation of emotions (Weber, 2006).

2.2.3.3. Language and Meaning

This section deals with: 1) the various terminologies used by different disciplines that intersect in decision-making on climate change; 2) the relationship between technical and everyday definitions exercised in the decision-making process and 3) the use of narratives to communicate meaning, values and experience.

The previous sections emphasise that decision-making processes need to accommodate both specialist and non-specialist meanings of the concepts they apply. Previous IPCC reports have provided technical definitions for a range of such terms in order to focus climate research and provide rational policy advice. However, the decision-making process surrounding vulnerability and adaptation assessment is broader than the technical aspects addressed in IPCC definitions and language (Adger, 2003; Füssel, 2007; O'Brien et al., 2007). Various disciplines often have

different definitions for the same terms or use different terms for the same action or object, which is a major barrier for decision-making (Adger, 2003). For example, adaptation is defined differently with respect to biological evolution, climate change and social adaptation.

Covering both technical and everyday meanings of key terms can help bridge the analytic and emotive aspects of cognition. For example, words like danger, disaster and catastrophe have technical and emotive aspects (Britton, 1986; Carvalho and Burgess, 2005). Terms where this issue is especially pertinent include adaptation, vulnerability, risk, dangerous, catastrophe and disaster. Other words have definitional issues because they contain different epistemological frames; sustainability and risk being key examples (Harding, 2006; Hamilton et al., 2007). (Budescu et al., 2012) found that people prefer imprecise wording but precise numbers when appropriate and that people's personal lexicons are very different so that uncertainty terms are interpreted very widely, and in the IPCC's case, differently to the uncertainty ranges intended. Many authors advocate that narrow definitions focused solely on climate need to be expanded to suit the context in which they are being used (Huq and Reid, 2004; O'Brien et al., 2007; Schipper, 2007).

The language of risk, because of its central role in decision-making on climate change, is especially important. Risk is a polyseme, a word with multiple, related meanings. A definition of risk therefore needs to encompass its polysemic nature, which technical definitions generally do not (Hansson, 2004). Meanings of risk range from its ordinary use in everyday language to power and political discourse, health, emergency, disaster and seeking benefits. Meanings range from specific local meanings to broad-ranging concepts such as the risk society (Beck and Ritter, 1992; Beck, 2000; Giddens, 2000). Thus, the hierarchy of approach, methodology and methods presented in Section 2.1 can be used to organise such differences in meaning and use.

Linguistic studies conclude that dictionary definitions are inadequate for communicating the complex framings involved in the word risk (Fillmore and Atkins, 1992; Hamilton et al., 2007), finding much richer meanings in text databases. The word risk occurs as both a noun and a verb and reflects harm and chance with negative and positive senses (Fillmore and Atkins, 1992). Hamilton et al. (2007) found an emphasis on health with no overwhelmingly negative or positive tendencies. Informal use tended towards personal risk, whereas formal use was more abstract, being technical and pedagogical. *The only observable pattern is the association with some form of assessment of the risk involved and the uncertainty that defines this assessment* (Hamilton et al., 2007).

These studies suggest that people do assess risk, balancing likelihood and outcome in a similar manner to formal risk assessment, confirming that risk, at least when consciously applied, forms the core of decision-making under uncertainty. The broad, generic description revealed by linguistic analysis is also consistent with the recent move in the risk literature to broad definitions of risk away from narrow technical definitions (Rosa, 2003; ISO, 2009).

In complex situations, the change between the problem-oriented component of risk assessment to the solution-oriented component shows the wording risk changing from a noun to a verb. Problem analysis applies risk as a noun (at-risk), whereas risk management applies risk as a verb (to-risk) (Jones, 2011). This reflects a change from core risk types of Hamilton et al. (2007) such as *asset* and *harm* associated with at-risk to *action* and *agent* associated with to-risk. For simple risks this transition is straightforward, and can be assessed using linear methods because of agreement around values and agency.

In complex situations, problem risk (at-risk) and solution risk (to-risk) compete with each other, often becoming amplified socially and leading to action paralysis (Renn, 2011). For example, unfamiliar adaptations that are themselves risky will force a comparison between the risk of maladaptation and future climate risks, echoing the risk trap identified by Beck where problems and 'solutions' come into conflict (Beck, 2000). Decision support for such complex risks needs to allow for the emotive and cognitive aspects

Much mental representation and subsequent expression is non-verbal. Language is but not the only tool important for communication and learning: visualization, kinetic learning by doing and other sensory applications can be used to communicate science, art and through play (Perlovsky, 2009; Radford, 2009). Much of this is carried out through various narratives. Narratives are accounts of events with temporal or causal coherence that may be goal directed (László and Ehmann, 2012). They range between being individual to organizational and institutional to cultural

narratives and are an innate property of the expression of mind in communication with one's-self or another. As such they are a "tool or process for making sense of events" (Gephart Jr, 1991) and have a strong role in creating social legitimacy. Narratives of issues such as climate change evolve over time and have a great influence on shaping public debate (Hamblyn, 2009).

Two aspects that scientific and adaptation narratives aim to address are (Cohen, 2011; Jones et al., 2013):

1) The transferral of knowledge and ideas to increase agency
2) The responses at an individual/institutional level to an aspect of adaptation, and communicate that experience with others.

The first aspect translates specialist knowledge into a common understanding so that actions can be implemented through a set of discursive frames (Juhola et al., 2011). This narrative bridges the route between scientific paradigm and adaptation methodology. This is often achieved by working with multiple actors in order to creatively explore potential solutions.

The second aspect concerns the stories that relate people's own responses to climatic impacts and other aspects of change (Bravo, 2009; Cohen, 2011). This is a complex area, as the narratives that inform these narratives relate strongly to identity, culture and perceptions of risk and are context specific. They provide the social construction within which decisions may be applied and also inform the nature of responses to future climate events. For example, a community that believes itself to be resilient and self-reliant is more likely to respond proactively, contrasted to a community that believes itself to be vulnerable (Jones et al., 2013). Bravo (2009) maintains that narratives of risk and vulnerability demotivate indigenous peoples whereas scientific and active citizenship narratives provide a framing that promotes resilience.

2.2.3.4. Ethics

The field of climate ethics has been developing over the last 20 years (Jamieson, 1992, 1996; Gardiner, 2004; Gardiner et al., 2010), resulting in a substantial recent literature (e.g., Garvey, 2008; Harris, 2010; O'Brien et al., 2010; Arnold, 2011; Brown, 2012; Thompson and Bendik-Keymer, 2012). Climate ethics can be considered as a social technology used to formalize values (Section 2.2.3.1) and rights into decisions, decision-making processes and actions.

However, the theoretical underpinning of climate change ethics, remains tenuous due to lack of experience, controversies and the complex nature of the problem. In climate change ethics the concept of vulnerability and adaptability do not concern only "nature", the land, in the sense of Leopold (1949), but also the ethical positions toward "some of the poorest and most economically disadvantaged societies of the world" (Pachauri, 2010; vii). It also concerns the co-benefits of the mitigation projects of developed countries (Pachauri, 2010). Climate ethics deals with scientific research results, economic as well as policy. It plays a fundamental role on global climate agreements and decision making.

Climate change can be considered as a primarily ethical question, because of important conflicts of interest (Broom, 2008) requiring complex ethical considerations at all levels. "The dominant discourses about the nature of the climate threat are scientific and economic. But the deepest challenge is ethical" (Gardiner, 2011; xii). The main ethical concerns include: intergenerational equity, distributional issues, scientific uncertainty, economic, policy decisions, international justice, low, voluntary and involuntary risk, cross-cultural relations, human relationship to animals and the rest of nature, technological and the socio-cultural worlds. From a philosophical perspective, climate change is related to environmental and ecological ethics, but previous ethical considerations did not have to consider the globality of the human condition, the distant future, nor the survival of humanity (Gardiner, 2011).

The notion of equity/inequity and responsibility are basic concepts in the United Nations Framework Convention on Climate Change (UNFCCC) Article 3 stating that "The Parties should protect the climate system for the benefit of the present and future generations of humankind, on the basis of equity and in accordance with their common but different responsibilities in respect to capacities" (United Nations, 1992).

Schneider and Lane (2006) distinguish three fields: (1) inter-country equity, (2) intergenerational equity, and (3) interspecies equity. Thomas and Twyman (2005) defined a 4th field, the intra-country or sub-national equity. A 5th topic on ethical factors concerns the necessity of a critical attitude toward future energy alternatives and, recently, geo-engineering. It is necessary to develop equitable solutions in view of protecting the most vulnerable groups and life forms (Wilkinson et al., 2007).

2.2.3.4.1. Inter-country issues

For CCIAV, the major discourse on equity is that the industrialized countries have caused most of the historical emissions, creating a natural debt (Green and Smith, 2002). There is an asymmetry between rich and poor nations concerning the higher impacts and greater vulnerability faced by developing countries and their lack of adaptive capacity with respect to developed countries. The neoclassic economic cost and benefit approach is ethically problematic because it does not cater for these differences (Broom, 2008). Recent policy developments at the international level involve the creation of an Adaptation Fund and fund for least developed countries, and include bilateral and multi-lateral aid agreements (Bouwer and Aerts, 2006; Clemencon, 2008).

2.2.3.4.2. Intergenerational issues

Intergenerational questions are frequently treated as an economic issue. The standard economic vision supposes that world economy grows continually, but important discussions (e.g., Nordhaus, 2007; Stern and Treasury of Great Britain, 2007) also relate to the duty to decide to act now (Stern, 2008). Future harm, and possibly catastrophe, may make the life of future generations difficult or impossible. These dilemmas involve ethical choices (Broom, 2008). Caney (2009) questions if the rights and interests of future people should be subject to a positive discount rate. Some philosophers consider that future generations can't defend themselves within current economic frameworks (e.g., Gardiner, 2011). Classical economics is based on Enlightenment notions and on the principle of abstract logic and disembodied rationality that cannot properly account for the dangers, interdependency and uncertainty under climate change (Nelson, 2011). Asymmetry between the present and future generations has changed: the future was once considered in the light of the past, now is considered in the light of the present (Bensaude-Vincent, 2009). Current economic discussions, in purely monetary terms, represent a unique view in history, as Gardiner (2011) stated, parents and grandparents did care about what they left to children and grandchildren, but this is not being reflected at the broader social scale.

2.2.3.4.3. Biotic ethics

Environmental ethics considers the decisions humans have to make concerning a range of biotic impacts (Schalow, 2000; Minteer and Collins, 2010; Nanda, 2012; Thompson and Bendik-Keymer, 2012). Some authors consider that up to 35% of the world's species could be in danger of extinction due to climate change's consequences (Thomas et al., 2004). These situations may require species relocation but 'assisted colonization' or 'managed relocation' but these proposals raise important ethical and policy questions. Minteer and Collins (2010) propose 5 key themes for decision making: 1. What criteria are used to select candidate populations? 2. How should these methods be combined with traditional ex-situ approaches? 3. Who should such decisions and implements them? 4. What are the key motivations and risks? 5. What constitutes environmental responsibility? Various claims are made for a more pragmatic ethics of ecological decision-making (Minteer and Collins, 2010) consideration of moral duties toward species (Sandler, 2009) and ethically explicit and defendable decision-making (Minteer and Collins, 2005a, b).

2.2.3.4.4. Intra-country inequity

Intra-country inequity relates to human and environmental exposure to risk or health impacts connected to climate change. Climate change ethics need to be further development in this field (Green and Smith, 2002). Of particular

concern are indigenous or marginalized populations who are often exposed to current climate extremes and natural disasters, with climate change exacerbating such ethical dilemmas (Tsosie, 2007).

2.2.3.4.5. Future energy alternatives and geo-engineering

Ethical issues on decision-making related to the fields of adaptation, mitigation or transformation due to climate change are emergent issues and are linked to economic and political decision-making. The limits of adaptation creating a case for geoengineering has come under recent consideration (Travis, 2010) and Chapter 19.

Another feature of climate change ethics concerns individual responsibility. Global climate change may also concern individuals who are 'world citizens'. Some authors advocate a new world ethics (Dower, 1998; Harris, 2010) consisting of moral values, norms and responsibilities applied globally. Cosmopolitan ethics and global justice can lead to successful mitigation and sustainability (Caney, 2006; Harris, 2010) and lead to collective decision-making on public matters through voting procedures (Held, 2004). Climate ethics argue for the necessity of effective responsible and 'moral' decision-making and action, not only by governments but also by individuals (Garvey, 2008). Hansson (2004) maintains moral appraisal is required for evaluating risks and benefits in order to establish equity, especially in the face of uncertainty.

Although the climate change ethics literature is rapidly developing, the related practice of decision-making and implementation needs further development. Moral and ethical issues are discussed at length in WG III, Chapter 3 *Social, Economic, and Ethical Concepts and Methods*.

2.3. Support for Climate-Related Decisions

Growing understanding of the aspects of decision-making (Section 2.2) can improve support for CCIAV decisions. This understanding informs the elements and principles of effective decision support (2.3.1), methods for impacts and vulnerability assessments (Section 2.3.2), the provision of climate information and services (Section 2.3.3), and a wide variety of other applications (Section 2.3.4).

2.3.1. Elements and Principles of Effective Decision Support

Decision support (Section 2.2) consists of three types of elements: 1) **products**: tangible deliverables including data, maps, projections, models and tools; 2) **services**: activities, consultations, and other forms of interactions with decision makers; and 3) **support systems**: individuals, organizations, communications networks, and supporting institutional structures that provide decision support products and services (NRC 2009a). For example, the institution (IPCC) that produced this report represents a decision support system. Much of this report, including Section 2.3.2 below, describes decision support products. These products can be used to inform decision support services, such as those in Section 2.3.3.

_____ START BOX 2-2 HERE _____

Box 2-2. Managing Wicked Problems with Decision Support

A well-designed decision support process, combined with auspicious political conditions, can effectively address 'wicked' (Section 2.1) decision challenges.

The State of Louisiana faces a serious problem of coastal land loss, imperiling the region's economically vital fisheries and heightening the risk of storm surge damage to the City of New Orleans, facilities accounting for about 20% of U.S. oil and gas production, and one of the United States' largest ports (CPRA 2012). Previous efforts at comprehensive coastal protection had been stymied by, among other factors, numerous competing jurisdictions and stakeholders with a wide range of conflicting interests.

In the aftermath of Hurricane Katrina, the state embarked on a new coastal planning effort, this time with extensive decision support. The Louisiana state Coastal Protection and Restoration Authority organized an extension decision support effort with a network of about a dozen research institutions interacting with a 33-member stakeholder group consisting of representatives from business and industry, federal, state, and local governments, nongovernmental organizations and coastal institutions. In dozens of workshops over the course of two years, these stakeholders influenced the development of and interacted with a decision support system consisting of two parts: 1) a regional model that integrated numerous strands of scientific data into projections of future flood risk (Fischbach et al., 2012) and 2) a multi-attribute planning tool that allowed stakeholders to explore the implications of alternative portfolios of hundreds of proposed risk reduction projects over alternative sea level rise scenarios (Groves et al., 2012). This decision support system allowed decision makers and stakeholders to first formulate alternative risk reduction plans and then to visualize outcomes and tradeoffs up to fifty years into the future.

The resulting Master Plan for a Sustainable Coast passed the state legislature on a unanimous vote in May 2012. Deviating strongly from past practice, the plan allocates far more resources to restoring natural barriers than to structural measures such as levees. The plan balances between the interests of multiple stakeholders and contains some projects that offer near-term benefits and some whose benefits will be largely felt decades from now. Many participants and observers of this process credited the extensive analytic decision support for significant contributions to this plan.

_____ END BOX 2-2 HERE _____

The effectiveness of decision support can be judged by the extent to which it increases the likelihood that decision-relevant information is produced and incorporated into decision making. Effective decision support provides users with information they find useful because they consider it credible, legitimate, actionable, and salient (e.g., Jones et al., 1999; Cash et al., 2003; Mitchell, 2006; Reid et al., 2007). Such criteria can be used to evaluate decision support (CITE) and such evaluations lead to common principles of effective decision support, which have been summarized in National Research Council (2009b) as:

1) Begins with user's needs, not scientific research priorities. Users may not always know their needs in advance, so user needs are often developed collaboratively and iteratively among users and researchers.
2) Emphasizes processes over products. While the information products are important, they are likely to be ineffective if they are not developed to support well-considered processes.
3) Incorporates systems that link users and producers of information. These systems generally respect the differing cultures of decision makers and scientists, but provide processes and institutions that effectively link individuals from these differing communities
4) Builds connections across disciplines and organizations, in order to provide for the multidisciplinary character of the needed information and the differing communities and organizations in which this information resides
5) Seeks institutional stability, either through stable institutions and/or networks, which facilitates building the trust and familiarity needed for effective links and connections among information users and producers in many different organizations and communities.
6) Incorporates learning, so that all parties recognize the need for and contribute to the implementation of decision support activities structured for flexibility, adaptability, and learning from experience.

These principles can lead to different decision support processes depending on the stage and context of the decision in question. For instance, decision support for a large water management agency operating an integrated system serving millions of people will have different needs than a small town seeking to manage its ground water supplies. A community in the early stages of developing a response to climate change may be more focused on raising awareness of the issue among its constituencies, while a community with a well-developed understanding of its risks may be more focused on adjudicating trade-offs and the allocation of resources. Each community will have different decision support needs.

Attributes and Resources

Better decisions need to be actionable and effective. Actionable decisions require a clear plan of implementation, have buy-in from stakeholders and if required, an institutional and governance framework. Effective decisions should produce the intended outcomes over a prescribed of time. Outcomes are subject to how a system responds to the decisions that have been made combined with internally and externally-driven change processes. In a simple system, the response will be proportional to the action, but in a complex system, many other factors can intrude. A better decision in the short term may not prove to be better over the long-term if a system changes its behavior or the definition of what is considered positive, changes.

Supporting good decisions requires appropriate resources and attention to the various attributes of decisions. The latter may be grouped into two broad categories: problem-based and solution-based.

Problem-based attributes may include the extent to which a situation is simple or complex. In the former, climate may be the dominant stressor and direct cause and effect can be identified. In the latter, climate may be one of multiple drivers of change, system feedbacks are strong and where adaptive responses are likely to change how the system behaves. Problem-based attributes also include spatial, institutional and time scales. Spatial and institutional scales tend to be associated with top-down and bottom-up directions of assessment. Spatial scales range from local (bottom) to global (top) and institutional scale from local to international. Time scales are associated with short- and long-term as temporal scales and fore- and back-casting in terms of directional scale. These scales can combine in a variety of ways.

Solution-based attributes strongly utilize creativity (Torrance, 1988). Creativity, as part of innovation provides the flexibility to explore the solution space combining problem solving within the broader context of normative goals. Creativity can be linked to the decision-making process and innovation to the development and implementation of tools, both cognitive and technological. Recent research into creativity suggests that rather than being uncontrolled brainstorming where anything goes, creativity is developed through a process of disciplined acts that seeks alternatives within a pre-defined set of boundary conditions (Sternberg, 1988; Sawyer, 2007). For CCIAV these conditions include scientific plausibility and factors such as economic efficiency, distributive fairness, scalability and so on.

In all but the simplest problems, a decision support process will iterate between the deliberation and analysis steps shown in Figure 2-4 (in Sec 2.2.1.3), exercising both problem and solution-based attributes.

Effective decision making also employs resources including leadership, institutions, and knowledge.

Leadership has been described as the ability to motivate others to achieve a set of goals and can be a characteristic of an individual within a group, or an organization (Vroom and Yetton, 1973; Chemers, 1997). Lack of leadership has been identified as a barrier to adaptation (Moser and Ekstrom, 2010). Although there are several theories attached to leadership, the most relevant to CCIAV is situational or contingency theory where leadership style is tailored to fit the situation at hand. This fits the wide range of situations encountered within CCIAV. Situational theory describes how normative or positivist methods are able achieve a particular set of goals. It also undertakes descriptive assessment of how effective different leadership styles are in achieving their normative aims and proposes models based on those findings (Vroom and Yetton, 1973; Margerison and Glube, 1979; Vroom and Jago, 1988; Chemers, 1997). Leadership can be understood through its role in a particular organization or institution via management lens through how innovations implemented by an individual or organization are transferred to other actors. While the expression of leadership may be in the operational arena (e.g., through inspiration by example) its overall aims are generally considered to be strategic to transformational. Three important styles of leadership are transactional, based on a reward/penalty strategy, laissez-faire and transformational, leaders who state goals, develop plans and encourage others to achieve them in a variety of ways (Bass et al., 1996; Eagly et al., 2003).

Institutions have a large number of attributes that encompass the spectrum between defined roles and informal narratives. In some cases institutional change may be required if that institution is contributing to market failures associated with climate change, the perpetuation of unsustainable practises or maladaptation. Institutions in

opposition to responses on climate change also influence decision-making, especially that affecting mitigation policy. Institutions can also respond to particular decisions on a need basis as an actor without altering its identity or path in the process. Institutions also act at different scales – some will be actors, some will provide resources and yet others governance.

Boundary organisations that link different disciplines and or institutions are increasingly being recognised as important to CCIAV decision support (Guston, 2001; Cash et al., 2003; McNie, 2007; Vogel et al., 2007). *A boundary organization is a bridging institution that acts as an intermediary between science and policy, whose goal is to shape perceptions of salience, credibility and legitimacy of available information, and effectively balance any trade-offs among them. This organization carries out information functions, including communication with decision makers, translation of science, and mediation between different views of how to interpret new information*. To serve as this bridge, this organization requires the ability to recognize the importance of location-specific contexts (Ruttan et al., 1994), to create a forum in which information can be co-created by interested parties (Cash et al., 2003), and to facilitate the creation of boundary objects, such as scenarios, and model-based decision support systems (White et al., 2010). Adaptive and inclusive management practices are essential to the functioning of such organizations, particularly in addressing wicked problems such as climate change (Batie, 2008).They also provide a bridge between adaptation to climate and to other processes managing global change processes and sustainable development.

Knowledge is a cultural resource that people can draw from and may also be generated for specific decisions. Malaska and Holstius (1999) describe an Aristotelian approach to good decision-making that requires three kinds of knowledge: purpose and objectives, situational knowledge and knowledge about means and resources. Situational knowledge for CCIAV requires historical and current knowledge of the system and scenarios and/or forecasts of the future. Some of the main challenges for knowledge are to transfer information from specialised sources, such as the scientific knowledge of climate change, through to where it can inform decisions. Often the transfer requires a transformation from specialised statistical knowledge to a generalised form of everyday information, such as may be used by a market or public good climate service. Knowledge generation, demand and transfer are cross-cutting issues that have a huge bearing on decision-making processes.

These resources and attributes can be viewed in how they influence the decision process itself. Figure 2-5 divides the decision-making process into four stages: scoping, analysis, implementation and review, outlining institutional and leadership, and knowledge and information characteristics for each stage. The two loops reflect the loops in Figure 2-2. Most effort in CCIAV research has been put into the first two stages, whereas decision implementation and follow up have been minimal. This does not imply that the analysis stage is discounted – problem analysis and solution evaluation is a significant undertaking in any decision-process, but that is where most current assessments stop.

[INSERT FIGURE 2-5 HERE
Figure 2-5: Selected attributes and characteristics relevant to the decision-making process itself. The two loops in the decision-making process relate to the two loops in Figure 2-2.]

Figure 2-6 combines the time element in planning adaptation to climate change with a systems planning approach at the organisational level. The coping range of climate (covering the spectrum between thriving and tolerance) that a location or actor is adapted to will need to change over time if to avoid increasing vulnerability. The coping range for any activity, location or organisation may be unique. This is combined with scenario use, visioning and strategic planning carried out in an organisational environment. A simplified systems approach builds in levels of leadership with research and development, strategic management and operations. Resources and directions are fed down through the system and feedback detailing progress and exceptional circumstances fed back up. All levels take in the environmental information needed for decision-making and where they cannot make decisions within limits set, send that signal up the line. The risk of crossing a critical threshold may require actions grading from the exercise of different options, revisiting strategic directions or, in extreme cases, revisiting the original vision.

[INSERT FIGURE 2-6 HERE
Figure 2-6: Planning frameworks for climate change showing the coping range, changing climate, thresholds and vulnerability for a single-variable climate scenario with idealised adaptation pathways (top) shows with a systems planning framework for organizations showing how vision, strategy and action can combine in a reflexive manner.]

The cases that follow are intended to elaborate on the role and importance of these attributes and ways in which they may matter. The cases are intended to be examples of situations where decisions could not (or were not) reached and why and where there were effective decisions and why.

2.3.2. Assessing IAV on a Range of Scales

If the goal of decision-making on climate change is to manage climate risks, then decision-making needs to ensure this goal is being achieved. Progress in CCIAV has been gradual, evolving as the scientific understanding of climate change improves. A number of global initiatives are taking place to enable knowledge generation, transfer and use, including the Programme of Research on Climate Change Vulnerability, Impacts and Adaptation – PROVIA (PROVIA web site: http://www.provia-climatechange.org/), the Nairobi Work Programme on impacts, vulnerability and adaptation to climate change – NWP (NWP web site: http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php), and work by the World Bank and regional development banks (World Bank climate change web site: http://climatechange.worldbank.org/).

As noted in Section 2.3.1, boundary organizations contribute to knowledge transfer, and there are examples of such entities contributing to regional CCIAV assessments, including Great Lakes Integrated Sciences and Assessments Center – GLISA (GLISA web site: http://www.glisa.umich.edu/), the UK Climate Impacts Program – UKCIP (UK Climate Impacts Program, 2011), and institutions working on water issues in the U.S., Mexico and Brazil (Kirchhoff et al., 2012; Varady et al., 2012).

2.3.2.1. Assessing Impacts

Climate impact assessment draws on interdisciplinary studies that focus on the interaction between nature and society. An early description of impact models is found in Kates (1985), who summarize various case study experiences based on historic events in determining direct cause and effect, and then proposing a more interactive model, in which initial societal responses would lead to a different impact in the future for a similar climatic event. A short term adjustment could ultimately lead to longer term adaptation by societies, as illustrated for drought adjustment in the Great Plains of the United States, in which a 'lessening' of impacts was observed during subsequent drought events (Warrick, 1980).

Scenario-based climate impact assessments differed from assessments of observed events, however, in that it challenged prevailing models of stability in climate-society relationships. A number of cases of historic events identified how decision makers, when faced with an extreme weather/climate event, held on to old views of such relationships and pursued a 'muddling through' approach (Glantz, 1988). Impact assessment of future climate change would therefore challenge prevailing decision frameworks that implicitly assumed climate stationarity (Milly et al., 2008).

In order for scenario-based impact assessments to contribute to vulnerability and risk assessment, there needs to be a series of translations carried out. Scenarios of projected greenhouse gas concentrations are converted to changes in atmospheric conditions, subsequently to impacts without proactive adaptation, and finally, to an assessment of the effectiveness of various adaptation options. As discussed in Chapter 1, and Section 2.2.1.6, climate change scenarios themselves have changed dramatically since the 1980s with the continued evolution of climate models and emission scenarios. A new scenario process aims to provide Representative Concentration Pathways (RCP) and corresponding climate projections and socio-economic driving scenarios(van Vuuren et al., 2012) that can be used for impact assessments.

This series of translations requires the transformation of data across various scales of time and space, between natural and social sciences, utilizing a wide range of analytical tools created by different fields of study, including agriculture, forestry, water, economics, sociology, and systems modelling. For example, scenarios for climate variables such as temperature and precipitation need to be translated into scenarios or projections for biophysical and socio-economic impact variables such as food supply, coastal erosion, health outcomes, species distribution and so on. Establishing these connections and supporting the translation process is an important function of climate services, described more fully in Section 2.3.3.

The assessment of impacts leads to placing the projected changes within the context of local management and governance, and to anticipate how possible future changes in management and governance over the scenario time frame of 50–100 years might influence the linkages between climate change and the associated socio-economic consequences for the location being assessed. This represents a combination of top-down biophysical assessments of futures and bottom-up socioeconomic assessments of the past and present (Figure 2-7a,b). This inconsistency hampers assessments of future adaptation responses (see Chapter 16). An important challenge, therefore, is to construct impact assessments in which biophysical futures are superimposed on socioeconomic futures (Figure 2-7c). An ongoing effort to address this inconsistency is the construction of a new set of socioeconomic futures, known as Shared Socioeconomic Pathways (SSP), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012).

[INSERT FIGURE 2-7 HERE
Figure 2-7: Approach Used to Inform Adaptation Policy (modified from Dessai and Hulme 2004 (Dessai and Hulme, 2004).a – biophysical and socioeconomic assessments based on historical observations; b –biophysical impact scenario superimposed on historical socioeconomic condition; c – biophysical and socioeconomic assessments based on future scenario.]

More recently, a new generation of scenario-based impact assessments has emerged in which regional case studies are linking biophysical, economic and social analysis tools, in order to describe the interactions between projected biophysical changes and managed systems, assuming various responses by the actors of those managed systems. For example, Ciscar et al. (2011) estimated the costs of potential climate change impacts, without public adaptation policies, in Europe in four market impact categories (agriculture, river floods, coastal areas, and tourism) and one nonmarket impact (human health). They found that if the climate of the 2080s were to occur today, the annual loss in household welfare in the European Union resulting from the four market impacts would range between 0.2–1%. A similar study was conducted in the UK (Hunt, 2008). Net benefits were projected for tourism, health and transportation maintenance in winter, while net losses were projected for buildings and transportation infrastructure due to increased flood risk, and for residential water supplies in Southeast England. In the U.S., Backus et al. (2013) assessed national and state level GDP and employment impacts, assuming the SRES-A1B scenario across the range of climate projections from the CMIP3, incorporating direct impacts on water resources, direct responses to these impacts by agriculture and other water interests, and indirect responses through inter-state migration of affected populations. The combination of direct and indirect responses resulted in an average cumulative GDP loss of 1 trillion U.S. dollars for 2010- 2050.

Another recent innovation is the application of decision support tools within scenario-based impact and adaptation assessments. One example is an assessment of the ability of a community water system in British Columbia, Canada, to meet regulated in-stream flow requirements within scenarios of climate and forest cover changes. In this case, the decision tool used was the Water Evaluation and Planning System model. Of seven scenarios tested, the community water system failed in six scenarios due to projected climate impacts on local stream flow. The exception was the case where forest cover was depleted due to an insect epidemic, similar to what other regions in British Columbia have already experienced, and which is also a projected impact of climate change (Harma et al., 2012).

2.3.2.2. Assessing Vulnerability and Risks

The adaptation to climate change, disaster risk management, and resilience literatures all address the concept of vulnerability, defined as a susceptibility to loss or damage (Adger, 2006; Füssel, 2007), or, the propensity or predisposition to be adversely affected (glossary). Within IPCC AR4 Schneider et al. (2007) identified those vulnerabilities that might be considered 'key', and therefore potentially 'dangerous' (see glossary). What makes an impact 'key' depends on certain criteria related to the climatic event itself, but also to the location or activity of interest. Criteria related to the event itself include the magnitude and timing of the event, its persistence and reversibility, and the likelihood and confidence that the event would occur. In Chapter 19, persistence of conditions of high susceptibility to the climate event is identified as a vulnerability of the activity. Other aspects of the location or activity include its importance in supporting society, its exposure to the event, and its capacity to adapt.

Adaptive capacity has been defined as the ability to adjust, to take advantage of opportunities, or to cope with consequences (Adger et al., 2007; glossary). However, adaptive capacity is context specific, related to both availability of resources and strong governance measures (see Chapter 14). As noted in Section 2.2.2.1, recent experiences in developed countries, such as with the 2003 heat wave in Europe (Haines et al., 2006) and Hurricane Katrina in the USA (Committee on New Orleans Regional Hurricane Protection Projects, 2009) have led to questions about attribution of causes for weather and climate-related impacts. High property damage and loss of life occurred in both cases because of failures in support systems (e.g., flood defence structures, coordinated heat relief programs). In New Orleans, development choices over a lengthy period increased this city's vulnerability to hurricanes by destroying the region's natural flood defences (wetlands, cypress swamps) in favour of navigation channels and flood control levees (Freudenberg et al., 2009).

The concept of 'adaptation deficit' (Burton and May, 2004) may be applicable to cases such as Katrina. Adaptation deficit represents a gap between a deficient state of adaptation and a state of adaptation that avoids adverse impacts (Chapter 17, glossary). Barriers unrelated to scientific knowledge can hamper effective decision making (Adger and Barnett, 2009; Berrang Ford et al., 2011). This may help to explain why an observed hurricane or other weather or climate event can create surprising levels of damage within developed countries. It has also been related to 'residual impacts', which occur due to insufficient adaptation to current or future climate (IPCC, 2007).Within developing countries, Narain et al. (2011) consider the adaptation deficit to be within a larger 'development deficit'. IPCC (2012) cite other 'deficit' indicators, including a Disaster Deficit Index (impact of extreme event combined with financial ability to cope), structural deficit (low income, high inequality, lack of access to resources, etc.), and risk communication deficit.

This difficulty in parsing out the relative influences of climate and development patterns has been identified within assessments of observed trends in property damage from atmospheric extreme events. For example, recent increases in economic losses may be attributed to changes in probabilities of extreme events, changes in human development patterns (more people in harm's way) without changes in climatic extremes, or a complex combination of both (Pielke, 1998; Mills, 2005; Munich Re Group, 2011). IPCC (2012) concluded that increasing exposure has been the major cause, but a role for climate change has not been excluded. Similar challenges will influence assessments of projected damage trends within future scenarios of climate change and development. .

Assessing damage within future scenarios of climate change will require approaches that link both bio-physical futures and socio-economic futures, providing opportunities to expand scenario assessments beyond expressing future human behaviour only through the lens of population growth, GDP growth and discount rates. An example is the assessment of climate change effects on human health, including research-to-decision pathways, monitoring of social vulnerability indicators and health outcomes (English et al., 2009; Portier et al., 2010), and tools for enabling adaptive management (Hess et al., 2012). An example of a regional scale scenario-based vulnerability assessment incorporating sensitivity, exposure, impact and adaptive capacity is a case study for North Rhine-Westphalia in Germany (Holsten and Kropp, 2012). An example of a larger scale study is a vulnerability assessment of ecosystem services for Europe, in which future adaptive capacity was based on indicators from the SRES storylines(Metzger and Schröter, 2006).

It may be difficult to anticipate how a development choice taken in the current or near term could influence future vulnerability to projected climate change, hence the interest in the study of ***emergent risks***, which is the focus of the review in Chapter 19. Interactions between development pathways, climate change impacts, and climate change responses, could create situations for which there is little or no precedent. Assessments based on gradual shifts in mean conditions could underestimate future risk and consequent damage, suggesting the need for process-based methodologies that focus on enhancing resilience (see Section 2.4.2). An example of assessing this type of risk, and the costs and benefits of potential adaptation responses, is a resilience assessment framework for infrastructure networks (Vugrin et al., 2011; Vugrin and Turnquist, 2012).

2.3.3. Climate Information and Services

Climate Services are the link between generation and application of climate knowledge. There is a growing body of literature concerning the development of such services; on their history and concepts (2.3.3.1.); on decision support as its main feature (2.3.3.2.), and the policy implications of climate service as a global practice (2.3.3.3.).

As the concept of Climate Services becomes ever more relevant for the generation and application of climate information on local, regional and national levels; numerous questions arise for decision makers, stakeholders and other private or public users concerning climate variability, monitoring of risks and adaptation planning "as an important component of sustainable development" (Vaughan and Dessai, 2013). The Global Framework for Climate Services (Hewitt et al., 2012) sets as a goal to "enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy and practice on the global, regional and national scale" (http://www.wmo.int/pages/gfcs/index_en.php). Miles et al. (2006) define climate services with a strong focus on the connection between climate science and the public demand for information. But many other disciplines are needed to support the development and delivery of climate services. This extended reach, which includes social sciences, is still fragmented and weak. To support the development and delivery of climate services, more than climate projections and scenarios are needed; observations from a variety of sources are needed as well as case-specific communication skills.

While many countries have already established national and regional climate services or are on the way to do so, the literature shows significant differences in the evolution, organization and practice of Regional Climate Services in different countries and parts of the world. The development of Regional Climate Services in the US and parts of Europe is well documented, with an increasing focus on the aspect of communication and decision support. The European Environmental Agency EEA established a clearinghouse, which provides access to the European data centre on greenhouse gas emissions and climate change impacts, vulnerability and adaptation (http://www.eea.europa.eu/themes/climate/intro). It is linked to the European Climate Adaptation Platform, which provides legal and practical information of regional adaptation measures (http://climate-adapt.eea.europa.eu/). Examples for national and regional Climate Services are: Europe and Eastern Asia (Ebinger et al., 2010); Germany's Climate Service Centre CSC (http://www.climate-service-center.de/) and the HGF Regional Climate Offices (Schipper et al., 2009); the Swedish 'SweClim' (Rummukainen et al., 2004), or the UK Climate Impacts Programme (http://www.ukcip.org.uk/).

An awareness of the need for climate services in developing countries is also growing (Semazzi, 2011), which is reflected in an increasing body of literature mostly from science and technology studies on the migration of standardized regional climate models into the 'global South'. While in 2001 only around 21 countries were running regional climate models (RCMs), mostly in OECD states, there are today about 104 countries trained in using the PRECIS RCM (Edwards, 2010). These show considerable differences in size, scope and practise, ranging from large-scale administrative services to ad hoc interventions of research institutes (von Storch and Zwiers, 2012). Regional Climate Services are expanding from the global North to the global South, shifting from simple understandings of climate information covered by linear approaches to ever more complex and wicked problem situations, and finally, increasing in interdisciplinarity by incorporating the social and communication sciences.

2.3.3.1. Climate Services: History and Concepts

In the peer-reviewed literature, the development of North American climate services is well documented (Changnon et al., 1990; Miles et al., 2006; DeGaetano et al., 2010). The idea of establishing climate services on both national and regional levels resulted from the growing concern over the consequences of climate fluctuations and the difficulties to provide and to distribute adequate information. In the beginning, climate services were merely understood as an expansion of the tasks provided by weather services and similar operational organizations, mainly dealing with forecasts, seasonal outlooks, and assessments of risks in a mostly stationary but variable climate. As it turned out, this restricted and mainly technical understanding of those services were barely effective. For example, decision makers had difficulties understanding and using climate data for planning purposes (Changnon et al., 1990; Miles et al., 2006; Visbeck, 2008). Furthermore, data were delivered slowly and were of poor quality; there were problems in obtaining data on appropriate time and space scales, and there was an "inability to access available datasets held by the private sector, states, regional and some federal agencies" (Changnon et al., 1990).

Attempts were made to provide regional climate services with increasingly sophisticated methods, infrastructure, tools, and collaborations. Early definitions of the mission and scope of climate services focused on being user centric, on active research, data stewardship and effective partnership (National Research Council, 2001). More sophisticated and broader agendas understood climate services as a clearinghouse and technical access point to stakeholders, providing education and user access to experts; they should inform the climate forecast community of the information needs, and propose and evaluate adaptation (Miles et al., 2006). But those general definitions and approaches do not reflect the diverse origins of climate services, mainly the difference between private services aimed at specific consumer needs and public ones with a broader agenda.

This static approach does not reflect changing consumer needs or even natural climate change; instead of being supply-focused, public climate services need communicate in the highly challenging environment of technical and institutional networks, monitoring systems, and collaborations with other institutions, stakeholders and decision-makers, as DeGaetano et al. (2010) suggest. Historic approaches and concepts did not meet this challenge in an effective way, being too static, supply oriented and not recognizing the need to include other sciences and methods.

2.3.3.2. Climate Services: Practices and Decision Support

Decision support is an integral part of the climate service concept and is generally acknowledged among government agencies and researchers as necessary for its healthy functioning (Miles et al., 2006; DeGaetano et al., 2010). There is an intense discussion in the climate services literature about the role of decision-support and its products, services and support systems fuelled a growing awareness of the issue of how the supply of scientific information can be reconciled with user demands. These debates focus on the possibilities, ranges and modes of communication. Social-planner models of society and environment relations (Hasselmann, 1990) provide for example insight into the possible economic outcomes of maximal cooperation when properly embedded in an iterative process of contested assumptions. Critics argue that these models present science as a monolithic knowledge provider, free of conflicts about the quality of data and the nature of facts, which is supposed to provide decision-makers with cost-effective solutions for adaptation and mitigation (c.f. Nordhaus, 1991). In its pure form, this 'linear model' approach is said to reveal many deficits in how science, policy-makers and the public interact, so is considered to be inefficient and sometimes misleading (Pielke and Carbone, 2002; McNie, 2007; Pielke, 2007; Sarewitz and Pielke Jr, 2007; Meyer, 2011).

Instead, the dynamic relationship between information and knowledge supply and demand is considered as the focal point for a successful climate service; the supply of scientific information has to be reconciled with user demands in order to produce scientific information which is relevant and suitable for decision making (McNie, 2007; Moser, 2009; Romsdahl and Pyke, 2009; Kandlikar et al., 2011; Pidgeon and Fischhoff, 2011). Furthermore, the communication of uncertainty and risk play a special role in framing science, and scientific data have to be turned into useful information (Shafer, 2004). According to Moser (2009) decision support is a diverse set of meanings and definitions that has come to mean "processes of interaction, different forms of communication, potentially useful data sets or models, reports and training workshops, data ports and websites, engaging any level of governance, at

any stage in the policy- or decision- making process". For Regional Climate Services, this more dialogic approach challenges the communication process as suggested by the National Research Council (National Research Council, 2009a); instead of beginning with users' needs, it seems more useful to link users and producers to ensure that all parties are involved in order to find out what the needs actually are. It also seems counterproductive to seek institutional stability per se, as the NCR suggests; sometimes it is necessary to identify where institutions need to change and to be sufficiently flexible and/or robust to change in line with, and in response to, climate, social and ecosystem changes.

Capacity building remains a crucial problem, especially in the absence of knowledge and awareness. Educational levels, geographic relevance and scale of information or the status of science in society vary highly among stakeholders as does their abilities to use various types of knowledge. It is important to include here both users and providers of knowledge to ensure a successful learning process. This is also true for more informal educational dialog in form of schools, on the web, in zoos or museums. In any case, communications should also include how climate services can be used, as well as their limitations.

For Shafer (2004), the climate service is a "process of two-way communication" and "involves providing context that turns data into information". For von Storch et al. (2011), climate services are "knowledge brokers" that have to establish an effective dialogue between science and the public. This dialogic communication contains two main tasks: "One is to explore the range of perceptions, views, questions, needs, concerns and knowledge in the public and among stakeholders about climate, climate change and climate risks. The other task is to convey the content of scientific knowledge into the public, to media and the stakeholders. This includes communicating the limitations of such knowledge, the known uncertainties and the unknowable, as well as the limited role of science in complex decision processes."

These demands outlined in the discussion and evaluation of decision-support on the regional level rely on and strongly support interdisciplinary approaches, combining information gained from climate science with knowledge gained from the social and communication sciences.

2.3.3.3. The Geo-Political Dimension of Climate Services

An emerging body of literature from the social sciences is observing practices associated with climate knowledge expansion and the implications of this expansion within a policy-relevant context (Yearley, 2009; Grundmann and Stehr, 2010). Science and technology-inspired studies focus on the mobility of climate knowledge into the "global South' or developing countries. Decision support tools developed in universities in the global North such as the climate model PRECIS from the UK Met Office spread all over the world and serve as a link between the developed and developing countries seeking to adapt to future climates. Earth system models such as PRECIS contribute to capacity building in direction to regional or national climate change management. This mobility of knowledge at the interface of science and politics has far reaching implications for the shaping of global geographies of climate knowledge production; these models strengthen the influence of epistemic communities such as the IPCC and other global governance mechanisms (Mahony and Hulme, 2012). Thus, while regional climate models play an increasingly important role in decision making processes (Dessai et al., 2009), critics argue that climate becomes the focal point of planning and development strategies and renders local forms of knowledge subordinate to this 'climate reductionism' (Hulme, 2011).

A growing number of ethnographic studies of local or regional climates and cultures shows the increasing relevance of indigenous forms of knowledge for the practice of Regional Climate Services (Strauss and Orlove, 2003; Crate and Nuttal, 2009; Crate, 2011; Ulloa, 2011). Anthropological studies demonstrate that local forms of knowledge and scientific climate models are not necessarily mutual exclusive; instead, individual case studies show how both forms of knowledge inform each other to the benefit of a place based adaptation to climate variations (Strauss and Orlove, 2003; Orlove and Kabugo, 2005; Orlove, 2009; Strauss, 2009; Orlove et al., 2010). Indigenous knowledge for climate change adaptation was reviewed in IPCC AR4 (IPCC, 2007), in which various examples of local knowledge systems are now being applied to the newer challenge of proactive adaptation to projected climate change. This increased attention to oral histories is leading to new experiments in which these are compared or combined with

remote sensing technologies and model-based scenarios, to co-produce new knowledge, and to create a new discourse on adaptation planning (Nakashima et al., 2012). The challenge will be to carry out these collaborations in a manner that enables their integration into a holistic narrative on future adaptation choices.

A case study from high arctic Canada, demonstrates the initial incommensurability of Inuit and scientific observations of changing weather patterns (Gearheard et al., 2010), followed by a strong correlation when the appropriate phenomena for measurement and appropriate analyses are identified by meteorologists (Weatherhead et al., 2010). Nakashima et al. (2012) analyse how scientists tend to initially discount indigenous observations, when in actual fact, shortcomings in understanding may derive from the practice of science (see also the discussion in chapter 12.3). These cases show that adaptation is and needs to be local; Endfield (2011) argues for a 'reculturing and particularizing of climate discourses' in order to successfully localize global and scientific meta-narratives. The growing number of this kind of study reveals that one strategy will not suite every local situation, and that climate service development is indeed a dialogic process that challenges the knowledge basis of all sides involved.

Social, cultural and communication sciences play a decisive role in this process (Pidgeon and Fischhoff, 2011; von Storch et al., 2011). Cultural values, social actors, national and regional politics enter the stage; science becomes part and parcel of the negotiation process entailing mitigation and adaptation decisions on various scales. To position itself and to react according to the diverse demands, science-based climate services have to become "rooted in society" (Krauss, 2011). The climate science community does not necessarily takes the lead, but becomes part of an inter- and transdisciplinary process, where politics, culture, religion, values etc. become part of climate communication.

2.3.4. Climate-Related Decision Support in Practice

At the societal scale, decision-making generally aims to achieve multiple objectives. A watershed may be managed for domestic water supply, hydroelectricity, agriculture, navigation, recreation, and in-stream requirements for aquatic ecosystems. These may be influenced by requirements for flood control, including maintenance of engineered structures that control flow and levels of lakes, rivers and water storage for later use (dams, reservoirs, canals). A forested region can include timber supply areas, lands set aside for parks and wildlife habitat, and other lands managed to support biofuels. These may be influenced by changes in disturbance regimes (insects, disease, fire, invasive species), and requirements to protect endangered species.

Climate change could influence the achievement of these and similar management objectives. Recent literature on potential climate change effects on natural resources, public health and community planning and management is reviewed in chapters 3–12. As the complexity of management challenges increases due to development and other pressures, including climate change impacts, new decision-making paradigms are emerging. Examples include Integrated Water Resources Management (IWRM), Sustainable Forest Management (SFM), and Sustainable Fisheries Management.

Bates et al. (2008) briefly reviewed the IWRM, describeding it as a participatory process. Sustainability of ecosystems, demand management, and integration of water within social and economic development, would all be explicitly considered as part of a participatory approach to water and land resources planning and implementation (Agarwal et al., 2000; Snellen and Schrevel, 2004). Many countries have recently acknowledged IWRM principles (Garcia, 2008; Jønch-Clausen, 2010), but they contain implementation challenges that may be exacerbated by climate change effects on water cycles and extreme events. Jønch-Clausen (2010) gives examples for the state of Orissa, India and Martz et al. (2007) for the South Saskatchewan River Basin, Canada. Additional discussion on IWRM is found in chapter 3.

SFM aims to maintain and enhance the economic, social and environmental values of forests, but is still an abstract concept (Seppälä et al., 2009). This is in contrast to the more narrowly defined timber-dominant forest management (Wang, 2004). Criteria and indicators for SFM assessment have been identified (McDonald and Lane, 2004; Wijewardana, 2008; Montréal Process, 2009), focusing on biological diversity, productive and protective functions of forests (e.g. maintenance of soil and water resources), maintenance of social and economic benefits (e.g. wood

products, social and spiritual needs), and governance. Climate change is seen as relevant to achieving SFM objectives (Montréal Process, 2009), and consequently, climate change may pose new kinds of vulnerabilities and risks. An example of a vulnerability assessment is illustrated for a case study of SFM in the Austrian Federal Forests of the Eastern Alps (Seidl et al., 2011). At the same time, however, governments and companies are considering assisted migration as an adaptation strategy (Pedlar et al., 2012). Additional discussion of SFM is found in chapter 4.

Sustainable fishing is defined as long term fishing at an acceptable level of biological and economic productivity without leading to ecological changes that foreclose options for future generations (FAO, 2013). Climate change has generally not been included in strategic guidance for fisheries management (Brander, 2010). Industrial fishing has led to depletions of some populations (Pauly et al., 2002), and climate change would create additional stress on marine biodiversity through warming-induced species invasion in high latitudes, and local extinction in tropical regions (Cheung et al., 2009). Ecosystem-based fishery management or EBFM (Zhou et al., 2010), seeks a balance in exploitation of various species. This is complemented by emerging discussion on evaluating harvest management strategies, including a management strategy evaluation or MSE (Sainsbury et al., 2000; Bunnefeld et al., 2011) incorporating monitoring and model simulation of managed systems, enabling simulation of proposed decision rules. Additional discussion of fisheries management is found in chapters 3 and 5-7.

At the national level in the least developed countries (LDCs), National Adaptation Programmes of Action (NAPA) was an important initiative launched by the UNFCCC (2009). NAPAs must be action-oriented and country-driven and be flexible and based on national circumstances. The key preparatory steps include the synthesis of available information on vulnerability to and impacts of climate change and variability, via extensive public participation and consultation. The NAPA process has assisted least-developed countries to assess climate sensitive sectors and prioritize projects to address the most urgent adaptation issues for vulnerable regions, communities, and populations (Lal et al., 2012; UNFCCC, 2012). For example, Sudan prioritized projects through a two-part process of quantitative and consultative criteria and stakeholder involvement (World Resources Institute et al., 2011). The integration of NAPAs with other socio-economic programs can help develop resilience. Rwanda and Bangladesh linked their NAPAs and Poverty Reduction Strategy Papers (PRSPs) in order to facilitate mainstreaming of climate change adaptation. The Bangladesh NAPA also identified adaptation strategies that complimented the PRSP (OECD, 2009). Although many countries have linked their NAPAs with development programs, Hardee and Mutunga (2010) argue that they have not been entirely successful in aligning the NAPA priorities with existing national development planning processes. In this context, they cited ‘population pressure’, which is recognized as an issue for adapting to climate change but not incorporated into national adaptation planning or poverty reduction strategies.

Scaling up and institutionalization of the NAPA process has already begun. Under the Cancun Adaptation Framework developed at COP16, a process was established enabling LDCs to formulate and implement national adaptation plans (NAPs) that would build upon the NAPA experience (UNFCCC, 2013). The main objectives of the NAPs are to identify vulnerabilities, medium- and long-term adaptation needs and to develop and implement strategies and programmes to address those needs and also to mainstream climate change risks.

Many developed countries have made progress towards developing adaptation strategy documents at different levels of governance. Swart et al. (2009) analysed National Adaptation Strategies (NAS) of nine European nations examining their decision making aspects, finding both ‘top-down’ and ‘bottom-up’ (delegation of authorities to local governments) approaches. Dissemination of information on weather, climate, impacts, vulnerability, scenarios, etc. was found to be very critical elements for adaptation decision making. Swart et al. (2009) also identified multiple scales and actors involved in the adaptation decision-making process, these actors having different and contradictory views of adaptation measures.

Climate risk-based decision making is becoming an increasingly widespread practice in both developing and developed countries. For example, the aquaculture industry is rapidly developing in coastal Vietnam but the dikes and structures that protect this industry can be severely damaged by storm surges. In response, Vietnam has initiated large-scale mangrove restoration and rehabilitation programs with the support of international institutions (World Resources Institute et al., 2011). The Tsho Rolpa glacier lake in Nepal was at the risk of outburst due to rapid melting of the glaciers (Adger et al., 2007). Considering the risks, the Government of Nepal started implementing

both short- and long-term measures to prevent the outburst flood event (World Resources Institute et al., 2011). There are many instances of risk-based decision making in developed countries as well. Taking lessons from the 2003 heat waves that killed some 35,000 people across Europe, many European countries have already implemented health-watch warning systems (Alcamo et al., 2007; WHO, 2008).

Awareness of climate change risks has propagated to local levels in many countries. Some municipal governments are already embracing the idea of incorporating climate change adaptation planning within municipal planning instruments, including energy and water system design, disaster risk reduction and sustainability plans (Ford and Berrang-Ford, 2011; Rosenzweig et al., 2011).

Although there is a rapidly growing list of adaptation plans being generated at national and local scales (Berrang Ford et al., 2011), an evaluation of adaptation plans from Australia, United Kingdom and the United States suggests that these plans are largely under-developed. This reflects a preference for capacity building over the delivery of specific vulnerability-reduction measures, indicating that current adaptation planning efforts are still informal and ad hoc, with many institutions 'muddling through' the process (Preston et al., 2011). At the same time, however, anthropologists and other social scientists are documenting the growth in community-based adaptation initiatives, in part through climate change reception studies, which explore how local communities receive and act on climate change information (Baer and Risbey, 2009; Rudiak-Gould, 2011). Details of adaptation planning within urban and rural settlements are addressed in chapters 8 and 9, respectively.

Various enabling factors have been identified in stakeholder engagement processes. Such factors include access to human, social and economic resources, sharing observations and ICT tools (e.g., wireless broadband and wireless sensor networks, geographic information systems and Web based tools), high levels of local awareness, providing information allowing for good public understanding of stresses, risks and trade-offs, mainstreaming strategies, or political leadership and institutions. These factors allow new strategies to be explored and implemented (Shepherd et al., 2006). Enabling factors also include the availability of customized impact and vulnerability assessments for the community of interest and for local practitioners (engineers, planners, resource managers, political leaders) who would serve as champions for adaptation planning, and the existence of local social influences/networks and capacity that enable long term strategic planning and mainstreaming (Gardner et al., 2009; Cohen, 2010). These factors are further discussed in chapter 15 and 16.

Local government officials often lack training on climate change adaptation and require comprehensive guidance. To fill this gap, guidebooks have been produced, in which the process of adaptation planning is framed as both a team-building and project management exercise, activities that are already part of usual practice (Snover et al., 2007; Bizikova et al., 2008; ICLEI Oceania, 2008; CARE International in Vietnam, 2009; Ayers et al., 2012). Practitioner engagement in decision 'games' offers another training resource (Black et al., 2012).

Local scale visualization of impacts and adaptation measures, depicted on realistic landscapes, has become an emerging technology that is being tested to support dialogue on adaptation planning at the local scale (Schroth et al., 2011; Sheppard, 2012). Although visual representations of scenario-based impact assessments may be available for a location, scenario-based adaptation assessments are not, so artistic depictions of potential adaptation measures and outcomes are negotiated with local stakeholders. This kind of exercise is currently being tested in communities within Metro Vancouver, British Columbia, Canada (Shaw et al., 2009; Burch et al., 2010; Sheppard et al., 2011).

2.4. Linking Adaptation with Mitigation and Sustainable Development

2.4.1. Assessing Synergies and Tradeoffs with Mitigation

The IPCC AR4 explored interactions between adaptation and mitigation (Klein et al., 2007). Capacities to adapt and mitigate are driven by similar sets of factors, and opportunities for synergies may be available particularly for agriculture, forestry, urban infrastructure and some other sectors. However, the AR4 concluded that a lack of information made it difficult to assess these synergies.

Similarly, assessments of trade-offs were at an early stage. The AR4 cited some case studies which indicated that if both the effects of mitigation efforts on climate, and the costs of implementing mitigation measures were accounted for, any benefits from reduced climate change impacts (for example, on malaria) would be offset by losses due to reduced rates of economic growth. However, the general state of the literature was that information on trade-offs was scarce, since mitigation studies rarely addressed implications for adaptation, while adaptation studies did not assess implications for emissions ('adaptive emissions').

An illustration of potential trade-offs and synergies, created by individual adaptation and mitigation actions, are shown in Figure 2-8. The upper left and lower right quadrants illustrate trade-offs that can result from actions within particular local-regional circumstances. The potential of these trade-offs to indirectly influence other adaptation and/or mitigation outcomes do not necessarily mean that such actions should be omitted from a climate change response portfolio, but decision making could benefit from the availability of a quantitative analysis of such trade-offs. Recent literature on potential interactions between mitigation and adaptation is reviewed in Chapters 15 and 16.

[INSERT FIGURE 2-8 HERE
Figure 2-8: Adaptation – mitigation trade-offs and synergies (adapted from (Cohen and Waddell, 2009).]

Chapter 20 offers detailed discussion of recent literature on the relationship between adaptation, mitigation, and sustainable development. This includes sustainable risk management (Section 20.3.3). However, the central theme of Chapter 20 is the strategic objective of enhancing climate resiliency.

2.4.2. Linkage with Sustainable Development – Resilience

The idea that climate change response and sustainable development should be integrated within a more holistic decision framework has been broadly discussed, including within IPCC AR4 (Robinson et al., 2006; Klein et al., 2007; Yohe et al., 2007). Practical aspects are being explored as local and sub-national scale actors (such as municipalities, regional districts, states/provinces) seek to incorporate proactive adaptation within long-term official development plans. This has enabled local case studies to be initiated, engaging researchers and practitioners (planners, engineers, water managers, etc.) in scenario-based exercises, building local capacity to plan for a range of climate change scenarios (Bizikova et al., 2010).

Folke et al. (2010) argue that people and nature are interdependent systems, and adaptability is enhanced when actors can enable systems and places to absorb disturbance and reorganize while undergoing change, so as to retain the same function, structure and identity. In other words, this characteristic, known as resilience, is the capacity to change in order to maintain the same identity (see Glossary). The idea of climate-resilient pathways is a central theme of Chapter 20.

Assessment of resilience is described as an approach that focuses on identifying and understanding processes that produce thresholds for fundamental change in a system, and identifying where resilience resides (see Section 2.2.1.2). This can be learned through participatory processes with local experts (Tyler and Moench, 2012), or through system modelling. In an ecosystem study, for example, there would be an evaluation of local sources of exceptional productivity and biodiversity, and how well these sources confer resilience within larger ecoregions. This is being used in the Arctic to map local ecosystem resilience, and to assess future persistence of the capacity of these local sources to support resilience of larger ecoregions, within scenarios of climate change (Christie and Sommerkorn, 2012). Another example is resilience analysis of supply chains, as illustrated by the case of petrochemical supply chains exposed to a hurricane in south-eastern United States (Vugrin et al., 2011).

Enhancing resilience is seen as an important component of increased adaptive capacity. In King County (Seattle) Washington, USA, collaboration between researchers and practitioners enables translation of scientific information from the global scale to local conditions (Snover et al., 2007). This conveys local ownership on impacts and adaptation assessments that feed into long-term decision making, creating a climate plan that is meant to be flexible, adjusting to new information as it becomes available, and supporting permanent research and monitoring of local environmental changes and evaluation of results of actions taken (Saavedra and Budd, 2009).

The King County example describes a shared learning approach to promoting climate change adaptation without being solely focused on 'hard' (technology, infrastructure, etc.) paths. Strengthening adaptive capacity promotes resilience by creating a place-based constituency for long-term monitoring, evaluation and assessment of changing conditions, and of local system performance. However, King County already has strong adaptive capacity, and is well endowed with human and financial resources that could be engaged in proactive adaptation within long term sustainable development planning. Tschakert and Dietrich (2010) indicate that in regions with high and chronic poverty, coupled with low awareness of drivers of global change, there is a gap in understanding about adaptation as a process, and that tools are needed to enable anticipatory learning.

Part of learning about adaptation as a process that can promote resilience, is good communication about management paradigms within various disciplines and fields of practice, and how these paradigms can shift as awareness of climate change and global change increases. Adaptation can have unintended consequences, and so the concept of sustainable adaptation has been proposed (Eriksen et al., 2011). Sustainable adaptation considers effects on social justice and environmental integrity, challenging current (unsustainable) development paths rather than seeking adjustments within them. This concept would recognize the role of multiple stressors in vulnerability, the importance of values in affecting adaptation outcomes, and potential feedbacks between local and global processes.

Within renewable resource management, there has been a paradigm shift from a focus on exploitation to ecosystem stewardship, in which the central goal is to sustain ecosystem capacity to provide services that benefit society as a whole. Chapin et al. (2009) identify differences in characteristics between steady-state resource management and ecosystem stewardship, in that the former would aim to achieve ecological integrity through managing stocks, while the latter's goal would be attaining sustainability benefits through managing feedbacks. For example, with the growing interest in hydraulic fracturing (fracking) to increase production of shale gas, as a cleaner alternative to other fossil fuels, regulation and adaptive environmental management are the subjects of new research on planning and decision making approaches, given the potential for negative feedbacks on water resources. Cases include regulation of coal seam gas exploration in Queensland Australia (Swayne, 2012), and new institutional arrangements to integrate water and energy decision making in Northeastern U.S. (Scott et al., 2011).

For urban areas, Leichenko (2011) categorize 4 types of urban resilience studies: a) urban ecological resilience, b) urban hazards and disaster risk reduction, c) resilience of urban and regional economies, and d) urban governance and institutions. Boyd et al. (2008) promote resilience as a way of guiding future urbanization that would be better 'climatized'. The Asian Cities Climate Change Resilience Network is applying a resilience planning framework, with attention given to the role of agents and institutions (Tyler and Moench, 2012).

Further consideration of disaster risk reduction is provided through the Hyogo Framework for Action (HFA), which considers climate change as an underlying risk factor, and promotes integration of risk reduction and climate change adaptation (UNISDR, 2007). The HFA mid-term review includes discussion on progress and challenges in its implementation, and calls for guidance on good practice for risk assessments, and for effective synergies between national and local levels (UNISDR, 2011).

One recent approach is the concept of Climate Smart Disaster Risk Management (CSDRM). The CSDRM approach seeks to integrate social development with disaster risk management in order to enhance adaptive capacity and address the structural causes of poverty, vulnerability and exposure. Emphasis is placed on strategies to manage uncertainty associated with both the physical and societal nature of disaster risk, with ongoing national and regional consultations throughout Africa and Asia (Mitchell et al., 2010). In small island states, integration of disaster risk management and climate change adaptation is enabled through focused institutional coordination, greater engagement of stakeholders and promotion of community-based adaptation and resilience-building projects (UNISDR, 2012b). Similar initiatives are underway in urban areas (UNISDR, 2012a).

Chapter 15 provides more detailed review of literature on disaster risk reduction.

Beyond paradigm shifts within individual fields of practice, resilience is also being explored as an outcome of social contracts which underpin governance. O'Brien et al. (2009) use examples from Norway, New Zealand and Canada

to illustrate how resilience thinking would frame climate change as a challenge that does not easily fit into existing social contracts of individual communities and nation states, and that new types of arrangements may better serve the goals of resilience and sustainable development within the context of climate change.

Chapter 20 provides more detailed discussion on climate-resilient development pathways, as an explicit objective of long-term planning and decision making.

2.4.3. Transformation – How Do We Make Decisions Involving Transformation?

There is now a growing literature that highlights the importance of transformative adaptation, particularly in the context of a world where the global temperature target of 2°C is exceeded. A recent World Bank report (PIK, 2012), highlights the significant, non-marginal change possible in a '4°C world'. Such climate change outcomes are likely to require new approaches for adaptation decision-making (Stafford Smith et al., 2011). Similar arguments are made by Kates et al. (2012), who suggest that transformational adaptation may be required in situations where incremental adaptation may be insufficient. There is a growing, though still sparse literature that examines such transformational adaptation in different sectors and systems. For example, Rickards and Howden (2012) consider transformational adaptation in Australian agriculture.

Adaptation that is transformative marks a shift towards an approach that includes adaptive management, learning, innovation and leadership, among other elements (O'Brien, 2012). This can be observed in the many adaptation projects that emphasize learning about risks, evaluating response options, experimenting with and rectifying options, exchanging information, and making trade-offs based on public values using reversible and adjustable strategies (McGray et al., 2007; Leary et al., 2008; Hallegatte, 2009; Hallegatte et al., 2011). Learning is an essential element of decision-making that supports transformative change (Tschakert and Dietrich, 2010).

Previously in the chapter we have indicated that complex decision problems often require active stakeholder engagement and participation in the decision-making process. Irvin and Stansbury (2004) identify situations where participatory processes may be most effective for bringing about positive social and environmental change. Recently, Park et al. (2011) have proposed the Adaptation Action Cycles concept as a means to delineate incremental and transformative adaptation and the role of learning in the decision-making process. They suggest that decision-making processes dealing with incremental adaptation are different from those used for transformative adaptation. Supporting transformational adaptation may also require a close examination of the legal and regulatory structures underlying environmental and natural resource management; Ruhl (2010) identifies a number of factors that will determine the connection between environmental law and adaptation, (Craig, 2010) suggests how a flexible approach could support increasing resilience and adaptive capacity of socio-ecological systems.

Much of the existing literature examines gradual adjustment or accommodation to change, and therefore, as (O'Brien, 2012) argues, there is a need to develop a body of research that will provide insights into how systems and structures may be transformed in an ethical and sustainable manner for resilience. This would be accompanied by a revolution in education at all levels of society (O'Brien et al., 2013).

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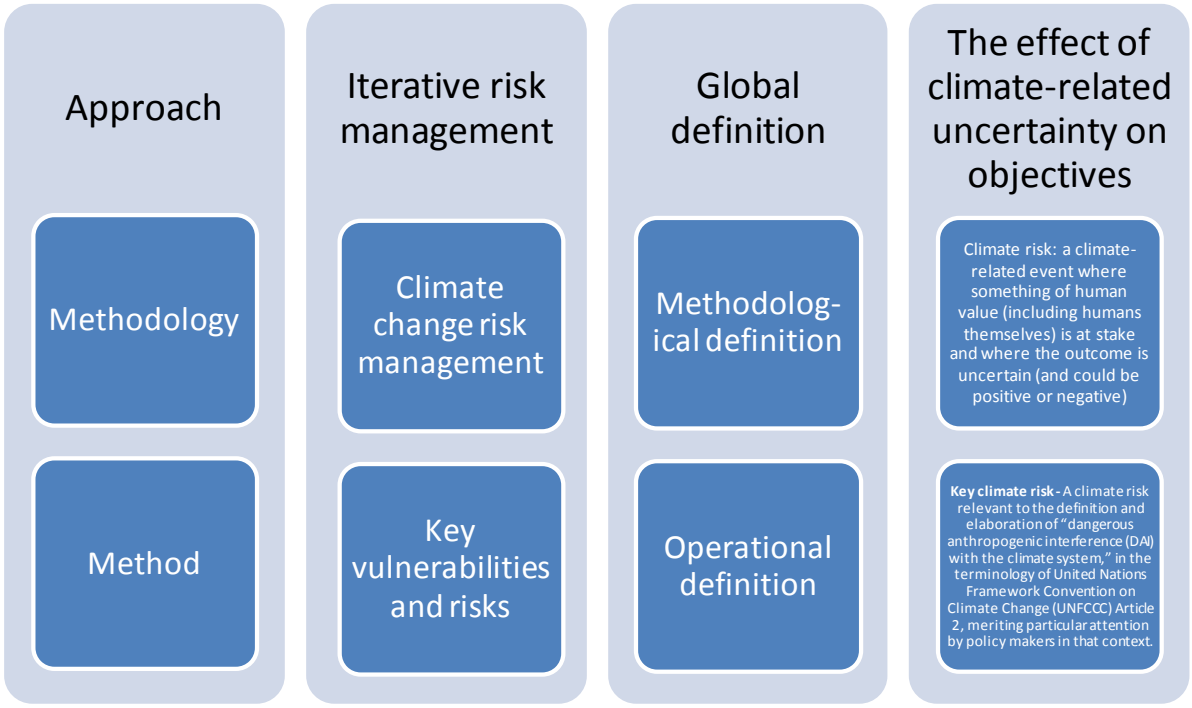

Figure 2-1: Risk portrayed as an approach, methodology and method using definitions relevant to this report.

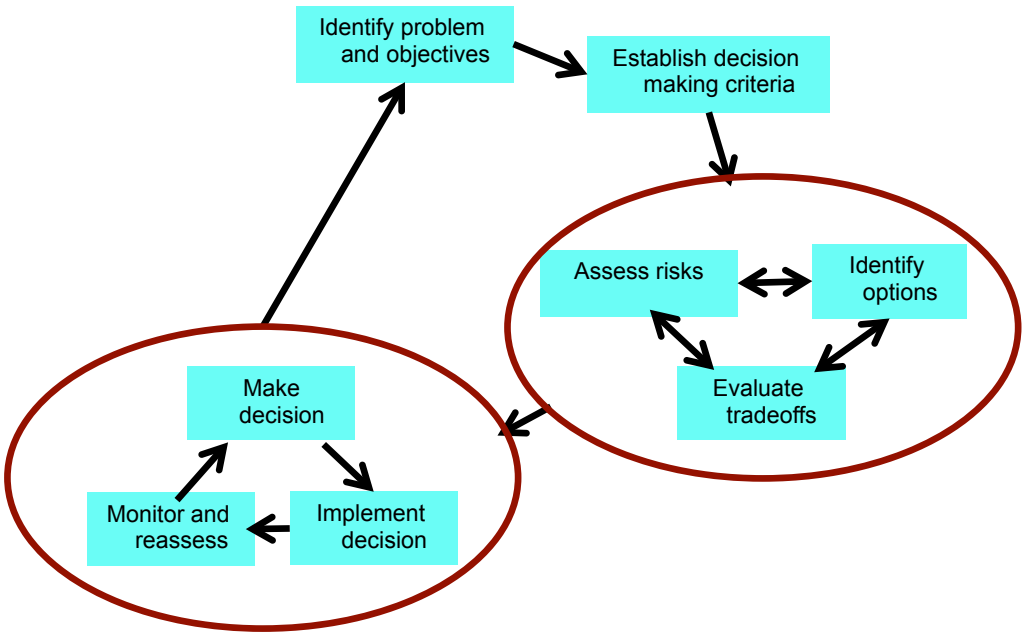

Figure 2-2: Iterative risk management framework showing two loops in the assessment process, looking at system feedbacks on options and at the risk management stage where a decision is made and implemented. Adapted from Willows and Connell (2003).

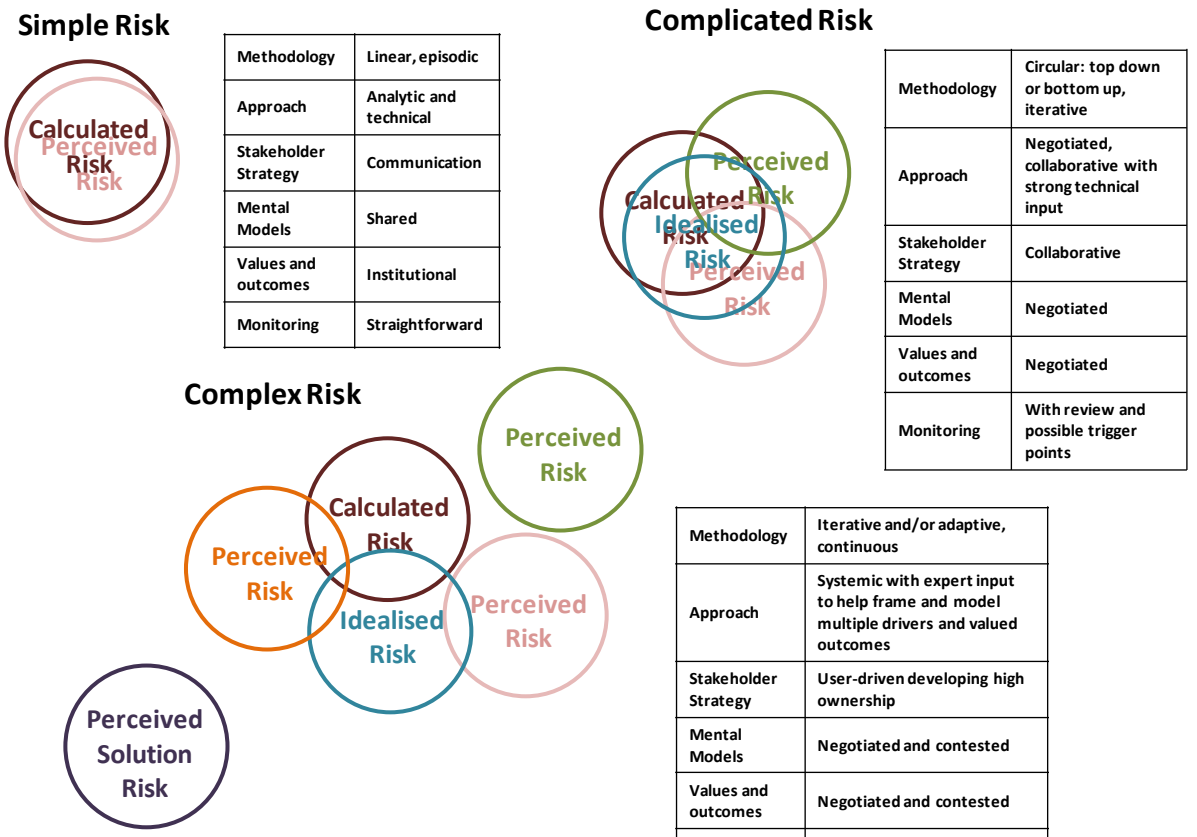

Figure 2-3: Schema for the chapter, showing a hierarchy of decision-makers in the centre and broad groupings of subjects addressed in the chapter. The decision-making environment is described by adaptation, mitigation and sustainable development, the methods and tools utilised include scenarios, decisions are made in the human context of individuals to groups and decisions can be assessed to measure varying degrees of success.

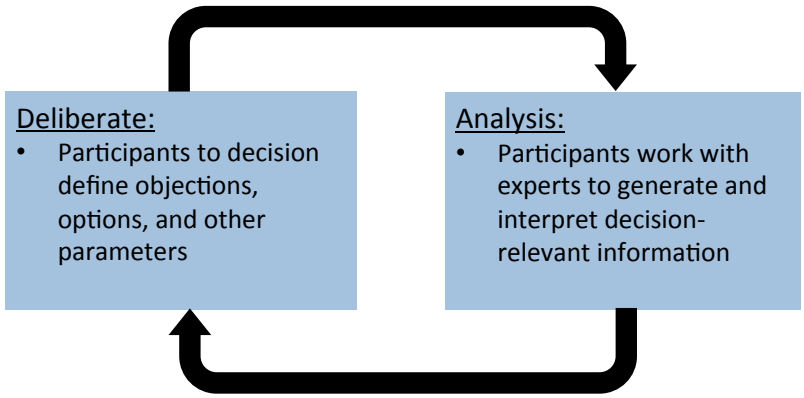

Figure 2-4: Deliberation with analysis decision support learning process.

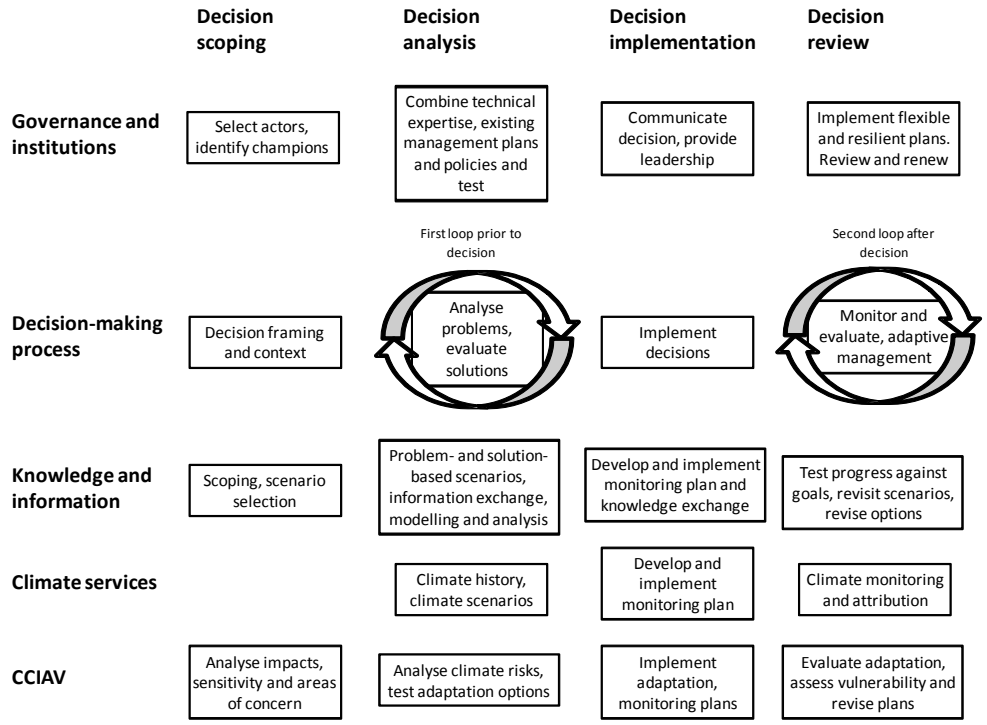

Figure 2-5: Selected attributes and characteristics relevant to the decision-making process itself. The two loops in the decision-making process relate to the two loops in Figure 2-2.

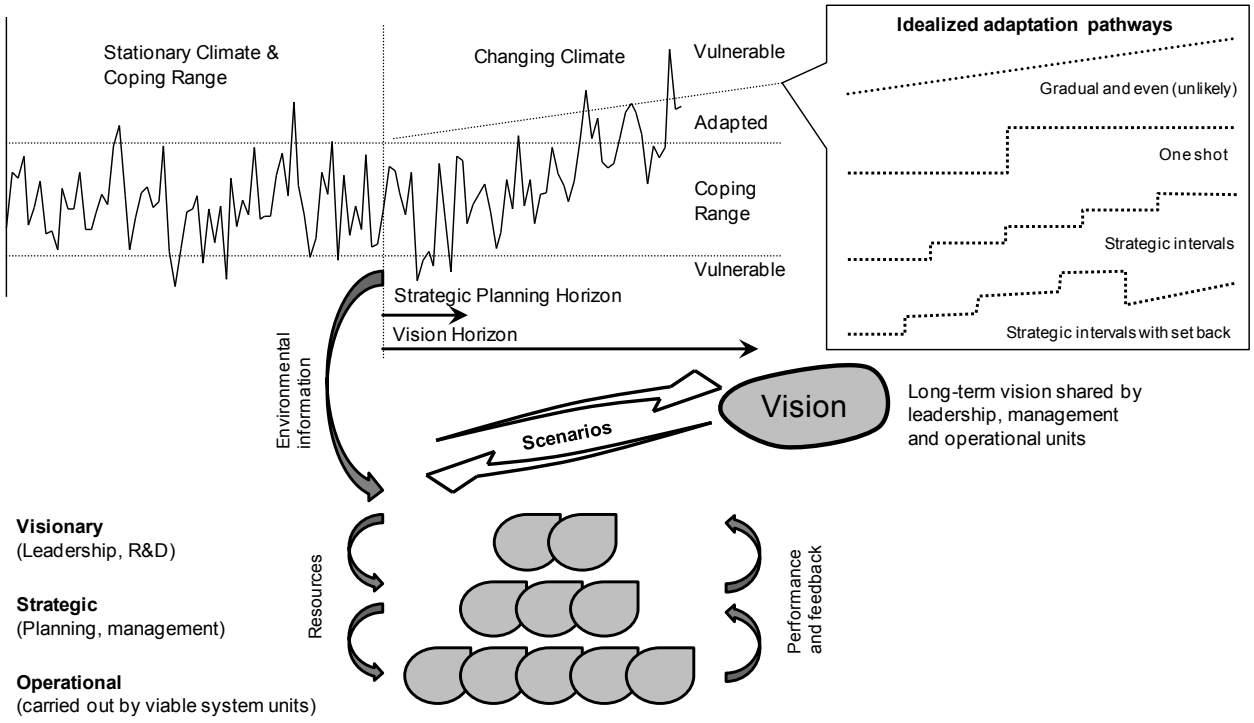

Figure 2-6: Planning frameworks for climate change showing the coping range, changing climate, thresholds and vulnerability for a single-variable climate scenario with idealised adaptation pathways (top) shows with a systems planning framework for organizations showing how vision, strategy and action can combine in a reflexive manner.

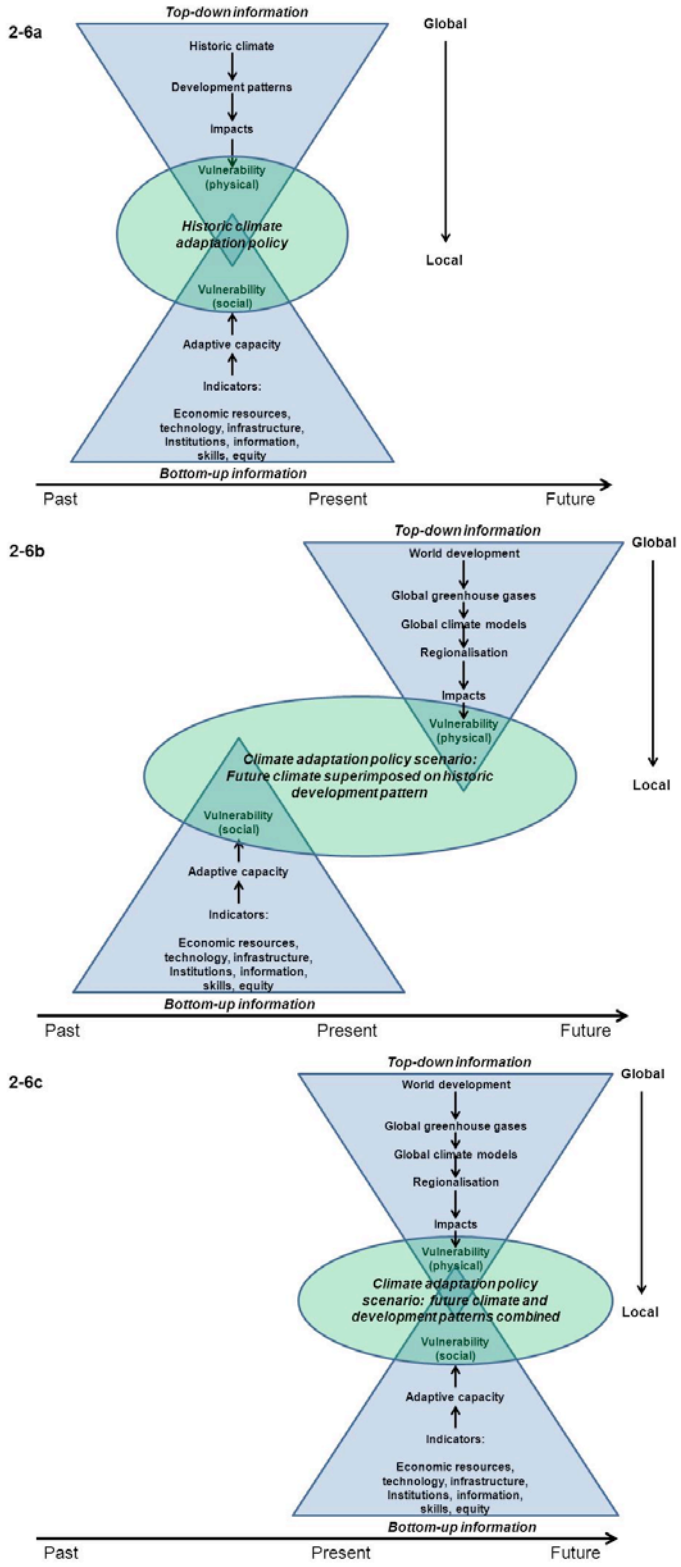

Figure 2-7: Approach Used to Inform Adaptation Policy (modified from Dessai and Hulme 2004 (Dessai and Hulme, 2004).a – biophysical and socioeconomic assessments based on historical observations; b –biophysical impact scenario superimposed on historical socioeconomic condition; c – biophysical and socioeconomic assessments based on future scenario.

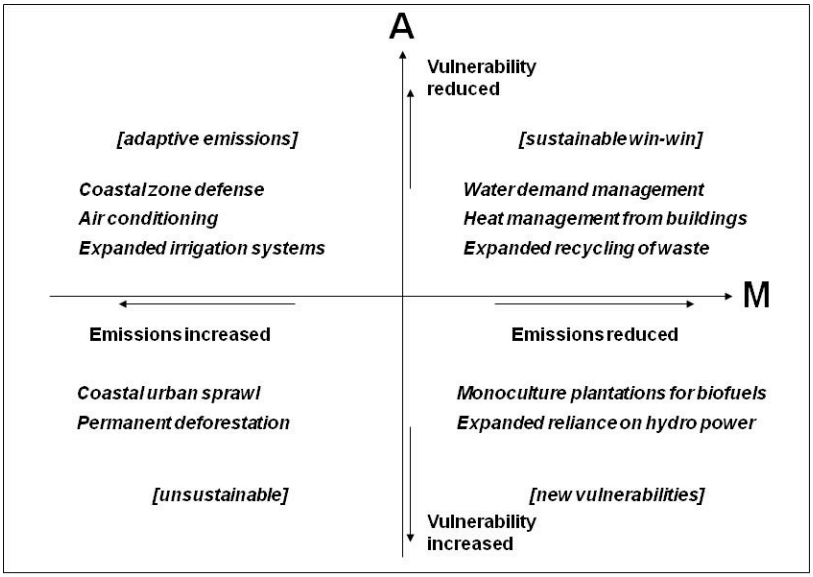

Figure 2-8: Adaptation – mitigation trade-offs and synergies (adapted from (Cohen and Waddell, 2009).

Chapter 3. Freshwater Resources

Coordinating Lead Authors
Blanca E. Jiménez Cisneros (Mexico), Taikan Oki (Japan)

Lead Authors
Nigel W. Arnell (UK), Gerardo Benito (Spain), J. Graham Cogley (Canada), Petra Döll (Germany), Tong Jiang (China), Shadrack S. Mwakalila (Tanzania)

Contributing Authors
Thomas Fischer (Germany), Dieter Gerten (Germany), Regine Hock (Canada), Shinjiro Kanae (Japan) , Xixi Lu (Singapore), Luis José Mata (Venezuela), Claudia Pahl-Wostl (Germany), Kenneth M. Strzepek (US), Buda Su (China), B. van den Hurk (Netherlands)

Review Editors
Pavel Kabat (Netherlands), Zbigniew Kundzewicz (Poland)

Volunteer Chapter Scientist
Asako Nishijima (Japan)

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Executive Summary

In the last decades, warming has caused a shift towards earlier maximum spring discharge, decreased spring snowpack and sometimes decreased magnitudes of snowmelt floods in regions with seasonal snow storage *(high confidence, high agreement, robust evidence)*. [3.2.3, 26.2.2] Where more winter precipitation falls as rain than snow, winter low flows have increased significantly. Where stream flow is lowest in summer, decreased snow storage has exacerbated summer low flows. River ice in Arctic rivers has been observed to break up earlier. [3.2.3]

Projected climate changes imply large changes in the frequency of floods *(high agreement, robust evidence)*. More frequent intense rainfall events (WG1 SOD 12.4.5.5) would increase the frequency of flooding in small catchments, but the implications for larger catchments are more uncertain because of the limited extent of the intense events. In some areas, reduced snowfall will reduce spring flood peaks. More people will be exposed to floods, notably in Asia, Africa, and Central and South America, and economic losses will increase due to both

increased exposure and anthropogenic climate change *(high confidence, high agreement, limited evidence)*. Vulnerability can be reduced by adaptation.

Projected climate changes would change hydrological regimes substantially *(high agreement, robust evidence)*. Runoff and groundwater recharge are projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions, controlled mainly by changes in precipitation. Changes in runoff are typically one to three times greater than changes in precipitation. Except in very cold regions, warming brings forward the snowmelt season, altering the seasonal regime. [3.4.5, 3.4.6]

Both increasing greenhouse-gas concentrations and climate change affect vegetation and thus transpiration, runoff and groundwater recharge *(high agreement, medium evidence)*. This impact is very uncertain and locally specific. The active role of vegetation is not considered in most hydrological studies. [Box CC-VW]

Glaciers will continue to lose mass, with meltwater yields from stored glacier ice eventually diminishing as the glaciers shrink *(high agreement, robust evidence)*. The rate of loss per unit of glacierized area will accelerate. The accumulation season will become shorter and the melting season longer, and in almost all regions total accumulation will decrease. In many regions meltwater production will increase during the next several decades but decrease thereafter. Glaciers have long response times and would continue to lose mass even if the climate were to cease to change. [3.4.4]

Drying of soils is projected in most dry regions *(medium confidence, high agreement)*. Projected changes in droughts depend partly on the definition of drought (WG1 SOD 12.4.5.3). [3.4.9]

Climate change is projected to reduce renewable water resources in most semi-arid and arid regions (*high agreement, robust evidence*). This constitutes a key risk, reducing food security. [3.5]

Climate change affects freshwater ecosystems by changing river flow regimes *(high agreement, limited evidence)*. Quantitative responses are known only in a few cases, but this ecological impact may be stronger than that of historic alterations due to human water withdrawals and dams. [3.5.2.4]

Certain approaches to reduce greenhouse-gas emissions imply greater risks for freshwater systems than others *(high agreement, limited evidence)*. Bioenergy crops can require larger amounts of water for irrigation than the amount of water for other mitigation measures. Hydropower has negative effects on freshwater ecosystems which can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk *(high agreement, limited evidence)*. [3.7.2.1]

Water quality changes are linked to warming, changes in rainfall, and climate-related erosion and deforestation (*high agreement, limited evidence*). Projections under climate change scenarios show a risk of deteriorating water quality for municipal supply, even with conventional treatment *(high agreement, limited evidence)*. [3.2.5; 3.5.2.3] Possible positive impacts include reduced risks of eutrophication and algal blooms when nutrients are flushed from lakes and estuaries by more frequent storms and hurricanes, *(high agreement, limited evidence)*. [3.2.5]

Climate change increases investment costs for water and wastewater treatment, while operating costs could rise or fall. Improved or even new water-treatment infrastructure may be needed to address variations in the quantity and quality of water *(high agreement, medium evidence*) but under warmer conditions water and wastewater treatment processes are likely to perform better *(low to medium agreement, limited evidence)*. [3.5.2.3; 3.6]

Hydrological impacts of climate change increase with increasing greenhouse-gas emissions *(high agreement, robust evidence)*. A low-emissions pathway reduces damage costs and costs of adaptation. Impacts of climate change on water resources are likely to reduce economic growth, particularly in developing countries (*high agreement, limited evidence*). [Table 3-2; 3.4; 3.5; 3.6.5]

Adaptive water management techniques offer an opportunity to address uncertainty due to climate change *(high agreement, limited evidence)*. Such techniques include scenario planning, employing experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. However, there are barriers such as lack of technical capacity, financial resources, awareness, communication, etc. [3.6.2; 3.6.6]

Adaptation to climate change in the water sector provides many opportunities for "no-regrets" improvements (*high agreement, limited evidence*). Of the global cost of adaptation, 85% is required in developing countries (*medium agreement, medium evidence*), in amounts similar to those estimated for the Millennium Development Goals [3.6.1; 3.6.5]. Annual global adaptation costs to maintain baseline levels of water-supply and sanitation services will be 50 to 70% of baseline investment in the sector (*high agreement, limited evidence)*. Some adaptive water-management measures also mitigate climate change (*medium agreement, low evidence*). For example wetland conservation increases carbon storage. [3.7.2]

3.1. Introduction

An adequate, secure water supply is essential for human well-being (Oki and Kanae, 2006), and changes in the hydrological cycle can generate different water-related hazards, and interact with non-climatic drivers and water management (Figure 3-1). Water is the delivering mechanism of climate change impacts to society even sectors on energy, agriculture, and transport. Even though water circulates on the Earth, it is a locally variable resource, and vulnerabilities to water-related hazards differ between regions.

[INSERT FIGURE 3-1 HERE
Figure 3-1: Framework for considering the impacts of climate change on freshwater systems and society. Socio-economic changes, such as GDP, population, and urbanization, will change the way of water managements, exposure and vulnerability of human beings against water related risks, and non-climatic drivers changing water management in terms of quantity and quality, as well as emissions and concentration of Green House Gases (GHGs) and Aerosol, that will lead to changes in precipitation, temperature, and sea level. Water management, non-climatic drivers, and climate change will alter hydrological cycles, and lead to change the impacts and risks for humans and ecosystems in conjunction with the changes in exposure and vulnerability, and hazards such as flood and drought. Water management consists with measures developing infrastructure, such as dykes, dams, and reservoirs, and non-structural measures, such as early warning system. Land cover and land use changes including afforestation, deforestation, and settlement, change of water demand due to economic development and demand changes in food and energy, and anthropogenic changes in pollutant load are examples of non-climatic drivers, and they are inter-acting each other. Mitigation acts on the emission and concentration of GHGs as well as on non-climatic drivers, while adaptation acts on non-climatic drivers and water management which alters exposure and vulnerability. (modified from Figure 3-1, AR4)]

Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, urbanization, economic development and land-use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation options for climate change can be seen positively as options for improvement.

The key messages with *high* or *very high confidence* from the Working Group II Fourth Assessment Report (AR4; IPCC, 2007) in respect to freshwater resources were:

- The impacts of climate change on freshwater systems and their management are mainly due to observed and projected increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semi-arid and arid areas are particularly exposed.
- Higher water temperatures, increased precipitation intensity, and longer periods of low flow exacerbate water pollution, with impacts on ecosystems, human health, water services reliability and operating costs.
- Climate change affects the water-management infrastructure and practice.

- Adaptation procedures and risk-management practices have been developed for the water sector in some countries and regions.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter assesses observed (Section 3.2) and projected future impacts (Section 3.4) of climate change on freshwater resources and their management, mainly based on research published since AR4. The drivers of hydrological change are summarized in Section 3.3. Impacts, vulnerabilities, and risks for human and environmental systems are assessed in Section 3.5; adaptation issues, including uncertainties and costs, in Section 3.6), and linkages with other sectors in Section 3.7. Current gaps in research and data are summarized in Section 3.8. For further information on observed trends in the water cycle, please see Chapter 2 of the Working Group I ("WGI") contribution to this assessment. See WGI Chapter 4 for freshwater in cold regions and WGI chapters 10 for detection and attribution, 11 for near-term projections, and 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4 below). Chapter 7 describes the impacts of climate change on food production (see also Section 3.5.2.1 for the impact of hydrological changes on the agricultural sector). The health effects of changes in water quality and quantity are covered in Chapter 11, and regional vulnerabilities related to freshwater in Chapters 21-30. Section 3.6.5 discusses impact costs and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Impacts of Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily an impact of anthropogenic climate change. Detection entails showing that part of the documented change is not due to natural random or quasiperiodic variability of the water cycle. For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human activities like water withdrawals, land-use change, pollution and water management mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic causes (Table 3-1). End-to-end attribution, from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies, because it requires experiments with climate models in which the external natural and anthropogenic forcing is "switched off". However climate models do not currently simulate the water cycle at fine enough resolution for attribution of hydrological impacts to anthropogenic climate change. Until climate models and impact models become better integrated, it is necessary to rely heavily on multi-step attribution, in which hydrological changes are shown to be consistent with climatic changes that may in turn be attributable to human activities.

[INSERT TABLE 3-1 HERE
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, which are not all known to be anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.

1: Gedney *et al*. (2006a), Gerten *et al*. (2008); 2: Piao *et al*. (2010); 3: Shiklomanov *et al*. (2007); 4: Hidalgo *et al*. (2009); 5: Collins (2008); 6: Baraer *et al*. (2012); 7: Rosenzweig *et al*. (2007); 8: Min *et al*. (2011); 9: Pall *et al*. (2011); 10: Aguilera and Murillo (2009); 11: Jeelani (2008); 12: Evans *et al*. (2005); 13: Marcé *et al*. (2010); 14: Pednekar *et al*. (2005); 15: Paerl *et al*. (2006); 16: Tibby and Tiller (2007).]

Extreme hydrological events, such as floods, prompt speculation about whether they are "caused" by climate change. Climate change can indeed alter the probability of a particular event. However, to estimate the alteration reliably it is necessary to quantify uncertainties due to natural variability in the changed and the unchanged climates, and also – because of the need for model simulations – uncertainties due to limited ability to simulate the climate.

The probability or risk of the extreme event can be measured by recording the fraction of events beyond some threshold. Call this fraction r_{ctrl} in the actual climate and r_{expt} in the climate in which there is no anthropogenic

climate change, and suppose there are many simulated, paired instances of r_{ctrl} and r_{expt}, with the ratio of risks given by $F = r_{expt}/r_{ctrl}$. The distribution of simulated risk ratios F is an estimate of the likelihood that the climate change has altered the risk.

Figure 3-2 illustrates the probabilistic character of attribution when uncertainty is multi-dimensional. It summarizes a formidable amount of computation, and it is not probable that such graphs will become routine tools for assessing single-event risks in, for example, the insurance industry. Nevertheless Figure 3-2 demonstrates consistency of weather with climate: anthropogenic greenhouse radiation made these floods much more likely. Reducing the computational cost of single-event attribution, possibly by identifying changes in event frequency, requires further study.

[INSERT FIGURE 3-2 HERE
Figure 3-2: Likelihood distributions of the ratio F of risks of flooding in England and Wales in autumn 2000 in several thousand paired simulations without and with anthropogenic greenhouse forcing (based on Pall *et al*., 2011; see also Bindoff *et al*., 2013 (WGI Chapter 10)). Each pair starts from a unique initial state that differs slightly from a common reference state. Vertical line represents no change in risk due to anthropogenic greenhouse forcing. Thin coloured lines: distributions with anthropogenic forcing, obtained with a seasonal-forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century; the forecast model is coupled to a model of basin-scale runoff and hydraulics. Thick black line: aggregate of the four distributions.]

3.2.2. Precipitation, Evapotranspiration, Soil Moisture, Permafrost, and Glaciers

Global trends in precipitation from several different datasets during 1901-2005 are statistically insignificant (Bates *et al*., 2008; Hartmann *et al*., 2013 (WGI Chapter 2)); however, according to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Baringer *et al*., 2010) and certain trends in total precipitation and numerous indicators of precipitation extremes are observed (Hartmann *et al*., 2013 (WGI Chapter 2)). Recent changes in regional precipitation are attributed mainly to warming, which alters the atmospheric circulation (Lambert *et al*., 2004; Stott *et al*., 2010). Although the models substantially underestimate observed trends, Zhang *et al*. (2007) estimated that in the 20th century anthropogenic forcing contributed significantly to observed increases in precipitation in the Northern Hemisphere mid-latitudes, drying in the Northern Hemisphere subtropics and tropics, and moistening in the Southern Hemisphere subtropics and deep tropics.

Changes in snowfall are indeterminate, as for precipitation, however, consistent with observed warming, a shortening of the snowfall season is observed for most of the Northern Hemisphere, together with shifts towards earlier start and later end dates of the snowmelt season (Takala *et al*., 2009; Tedesco *et al*., 2009).

On a global scale, evaporation increased from the early 1980s up to the late 1990s but not thereafter, although this appears to be due mainly to drying of land surfaces rather than to observed reductions of atmospheric evaporative demand (Jung *et al*., 2010). Observed and estimated global and regional trends in evapotranspiration suggest intensification of the hydrologic cycle (Huntington, 2010). Due to changes in precipitation, in diurnal temperature range, aerosol concentration, (net) solar radiation, vapour pressure deficit, and wind speed, the rate of regional pan evaporation has been steadily decreasing since the 1960s (Fu *et al*., 2009; McVicar *et al*., 2010; Miralles *et al*., 2011; Roderick and Farquhar, 2002; Wang *et al*., 2011). No fundamental physically-based explanation has been provided for the so called “evaporation paradox” that an increase in evaporation is expected, but a decrease has been observed (Fu *et al*., 2009). The evaporation paradox is made more puzzling by robust oceanographic observations of changes in geographical patterns of salinity. Salty parts of the ocean have become saltier and fresher parts fresher, a change attributable only to a more intense water cycle and, with *high confidence*, to human forcing of climate (Pierce *et al*., 2012).

Long-term records of soil moisture content in natural conditions are available in limited regions, such as the former Soviet Union, China, and central USA (Bates *et al*., 2008; Wang *et al*., 2011). Robock *et al*. (2005) reported a long-term increase in summertime soil moisture in Ukraine. Regional downward and upward trends in soil moisture

content have been calculated for China, where a trend to longer, more severe and frequent soil moisture droughts has been experienced over 37% of the land area (Wang *et al*., 2011). For example in South China, increases in dry days and a prolongation of dry periods have been detected (Fischer *et al.*, 2013; Gemmer *et al*., 2011), and can be attributed to increases in warm days and warm periods (Fischer *et al.*, 2011). These findings need to be considered carefully, as the results depend on the type of procedure used to obtain them (e.g. Sheffield and Wood, 2007).

Decreases in the extent of permafrost and increases in its average temperature are widely observed, for example in some regions of the Arctic and Eurasia (Comiso *et al*., 2013 (WGI Chapter 4)) and the Andes (Rabassa, 2009). Soil humidity in permafrost areas and permafrost degradation are strongly connected with the active-layer depth and influence the stability of steep slopes (Harris *et al*., 2009). The release of GHGs due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not well represented in global climate models yet (Grosse *et al*., 2011).

Due to glacier retreat, the formation of new lakes in high-mountain regions is increasing and causes further environmental impacts (Frey *et al*., 2010). As examples of changes on land, fast glacier length and area recession, thinning of the ice cover and an increase of regional snowline elevation are observed in South America (Rabassa, 2009). Almost all small glaciers in the tropical Andes have been shrinking rapidly since the 1980s; current rates are unprecedened since the early 18th century (Rabatel *et al.*, 2013).

3.2.3. Runoff and Stream Flow

There is a general agreement between detected trends in streamflow and the observed regional changes in precipitation and temperature since 1950s. In Europe, streamflow decreased in the south and east and generally increased elsewhere (Stahl *et al*., 2010; 2012), particularly in northern latitudes (Wilson *et al*., 2010); In north America increases were observed in the Mississippi basin and decreases in the US Pacific Northwest and South Atlantic-Gulf regions (Kalra *et al*., 2008). In China, a decrease in streamflow in the Yellow River is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze shows a small increase in annual runoff driven by an increase in monsoon rains (Piao *et al*., 2010). These and other stream flow trends must be interpreted with caution (Jones, 2011) because of confounding factors such as land-use changes (Zhang and Schilling, 2006), irrigation (Kustu *et al*., 2010) and urbanisation (Wang and Cai, 2010).

In a global analysis of simulated discharges (1948-2004), only about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay, and Niger) showed significant trends in discharge; 45 recorded decreases and only 19 recorded increases (Dai *et al*., 2009). Decreasing trends in low and mid latitudes are consistent with recent drying and warming in West Africa, southern Europe, South and East Asia, eastern Australia, Western Canada and the USA and northern South America (Dai, 2013). Global increase in runoff has been linked to reduced transpiration due to a decrease of stomatal opening of many plant species at higher CO_2 concentration (Gedney *et al*., 2006b). However, these results are disputed (Peel and McMahon, 2006).

In regions with seasonal snow storage, warming has caused a shift towards earlier maximum spring discharge (*high agreement, robust evidence*) and has increased winter low flows because more winter precipitation falls as rain instead of snow (Clow, 2010; Korhonen and Kuusisto, 2010; Tan *et al*., 2011). There is *robust evidence* of earlier breakup of river ice in Arctic rivers (de Rham *et al*., 2008; Smith, 2000). Where the stream flow is lowest in summer, decreases have exacerbated summer dryness (Cayan *et al*., 2001; Knowles *et al*., 2006).

3.2.4. Groundwater

Attribution of observed changes in groundwater level, storage or discharge to climatic changes is difficult due to additional influences of land use changes and groundwater abstractions (Stoll *et al*., 2011). Observed trends are largely attributable to abstractions and other human actions not related to climate change. To what an extent groundwater abstractions have already been affected by climate change is not known. Detection of changes in groundwater systems and attribution to climatic changes is rare, also due to a lack of appropriate observation wells

and a small number of studies. Observed decreases of the discharge of groundwater-fed springs in Kashmir/India were attributed to observed precipitation decreases (Jeelani, 2008, Table 3-1). A model-based assessment of observed decreases of groundwater levels in four overexploited karst aquifers in Spain led to the conclusion that groundwater recharge as a fraction of observed precipitation decrease declined during the 20th century. This allowed an attribution to observed temperature increase which caused increasing evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

3.2.5. Water Quality

Most studies published since the AR4 on observed impacts of climate on water quality refer to surface water bodies in high income countries, and cover intervals between 1 and 80 years. Some observed impacts of climate change on water quality are included in Table 3-1. Data for water quality is scarcer than for quantity. Impacts on water quality are linked to either seasonal or interannual variations in any of several variables, including ambient temperature, water temperature, precipitation and precipitation intensity. Droughts and the El Niño Southern Oscillation (ENSO) phenomenon can also affect water quality.

For lakes and reservoirs, the most frequently reported impacts are more intense eutrophication in warmer temperatures, shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*medium to high confidence, high agreement*). Higher runoff additionally results in higher loads of salts, faecal coliforms, pathogens and heavy metals (Paerl *et al.*, 2006; Pednekar *et al.*, 2005; Tibby and Tiller, 2007) (*medium to high confidence, medium to high agreement*; depending on the pollutant). Pathogens have associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by about 10% when turbidity increased in the influent of a drinking water plant during high rainfall events, even though the water was treated in compliance with standards (Emelko *et al*., 2011; Schwartz *et al*., 2000) (*high agreement* based on *limited evidence, medium to high confidence*). In a reservoirin Spain (Marcé *et al.*, 2010), stream flow variations were of greater significance than temperature increasesin depleting the dissolved oxygen content. Possible positive impacts on water quality include reduced risks of eutrophication and algal blooms when nutrients are flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl *et al*., 2008).

For rivers, all of the reported impacts reduced water quality. Greater runoff, instead of diluting pollution, sweeps pollutants , such as sediments, nutrients, organic matter, pathogens, salts and nutrients, from the soil into watercourses (*medium confidence, medium to high agreement*) (Benítez-Gilabert *et al*., 2010; Gascuel-Odoux *et al.*,2010; Howden *et al*., 2010; Loos *et al*., 2009; Macleod *et al*., 2012; Saarinen *et al*., 2010; Tetzlaff *et al.*, 2010). Some pollutants reduced dissolved oxygen concentrations. Increased organic matter content frequently impairs the quality of conventionally treated drinking water (Weatherhead and Howden, 2009) (*medium confidence, high agreement*). In streams in semiarid and arid areas, temperature changes have more impact than precipitation changes on the content of organic matter, nitrates and phosphorus (Benítez-Gilabert *et al.*, 2010; Chang, 2004; Ozaki *et al.*, 2003) (*medium confidence, medium agreement*).

Studies of groundwater quality are still limited. There are reports of elevated concentrations of faecal pollutants during the rainy season or after extreme rain events (*medium to high confidence, high agreement*), with varying response times. Due to impacts on health and the widespread use of groundwater for municipal supply this is an increasing source of concern (Jean *et al.*, 2006; Seidu *et al*., 2013). Faecal pollution during dry periods is extremely variable (Tetzlaff *et al.*, 2010), making any assessment difficult.

Linkages between observed effects on water quality and climate variability should be interpreted cautiously, at a local level, considering the type of water source and pollutant, the hydrological regime and the sources of pollution (*high confidence, high agreement*). Relationships between water quality and climatic variables are non-linear (except for temperature) and time-dependent (*medium confidence, medium agreement*). The pristine states of water systems need to be understood, since water sources are impacted upon for many reasons and effects may be long-lasting (Benítez-Gilabert *et al*., 2010; Howden *et al*., 2010; Kundzewicz and Krysanova, 2010; Senhorst and Zwolsman, 2005; Ventela *et al.*, 2011; Whitehead *et al*., 2009a). If the observed deterioration of water quality

continues, measures already in place to control point and non-point sources of pollution may be inadequate to deal with the negative impacts of climate change (*medium confidence, high agreement*).

[INSERT FIGURE 3-3 HERE
Figure3-3: Observations and projections of the impacts on the quality of water. (Note: This is not the final figure, it is still under production.)]

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne *et al*., 2012; their Table 3-2), which is expected to increase rainfall erosivity and to enhance soil erosion and sediment load. Warming may affect soil moisture, litter cover and biomass production, bring about a shift in winter precipitation from non-erosive snow to erosive rainfall, and increase melting of permafrost (Kundzewicz *et al*., 2007). The effects of climate change on soil erosion and sediment load are frequently obscure by impacts of human activities on river catchments (agriculture land use, grazing, water management; Walling, 2009).

In the Yellow River basin, where soil erosion results mostly from heavy rainfall events, reduced precipitation has contributed about 30% to a total reduction in sediment yield during 1970-2008, the remainder being attributable to water abstraction, sediment trapping in reservoirs and soil conservation measures (Wang *et al*., 2007; Miao *et al*., 2011). Dai *et al*. (2008), analyzing the decrease in sediment discharge of the Yangtze River over 1956-2002, found that climate change is responsible for an increase of about 3±2%, although on the side sediment decline dam construction (Three Gorges Dam) contributed 88±10% and soil conservation measures 15±5%.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with accelerated ice retreat either at high altitude or latitude (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive; there are both decreasing (e.g. Iceland; Lawler *et al*., 2003) and increasing trends (Patagonia; Fernandez *et al*., 2011). In the Himalayas and Tibetan Plateau, glacier areas have shrunk about 2-10% over the past 45 years but sediment yields from the Hindu Kush-Himalayas have decreased by half since the 1980s (from 4.3 Gt/year before the 1980s to <2.1 Gt/year; Li *et al*., 2008) due to intense human activities at altitudes below 500 meters (e.g. sediment retention in dams).

Detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology. So far, there is no clear evidence that the frequency or magnitude of shallow landslides has changed over past decades (Huggel *et al*., 2012), even in regions with relatively complete event records (e.g., Switzerland; Hilker *et al*., 2009). Increased landslide impacts (measured by casualties or losses) in south, east, and southeast Asia, where landslides are predominantly triggered by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *low confidence* with *limited evidence* that anthropogenic climate change has made a significant contribution to soil erosion, sediment loads and landslides. The available records are limited in space and time, and evidence suggests that, in most cases, the human impacts are more significant than the impacts due to climate change.

3.2.7. Hydrological Extremes and Their Impacts

There is *low confidence*, due to *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale. The lack of robust evidence is mainly due to lack of long-term records from unmanaged catchments, most of those available being from headwaters, and the difficulty of attributing detected changes to climate or to human activities (Section 3.2.1). However, recent detection of changes in extreme precipitation and discharge trends (at some catchments) suggests an increased likelihood of flooding at regional scale (*medium confidence*). More locations and studies show increasing trends in heavy precipitation than those

recording a decrease (Seneviratne *et al*., 2012), and flood-damage costs worldwide have been increasing since the 1970s, although partly due to increasing exposure of people and assets (Handmer *et al.*, 2012).

There is no strong evidence for trends in flooding in the USA (Hirsch and Ryberg, 2012), Europe (Benito and Machado, 2012; Kundzewicz, 2013; Mudelsee *et al*., 2003), UK (Hannaford and Hall, 2012), South America, and Africa (Conway *et al*., 2009). However, at smaller spatial scales, increases in flood magnitude and frequency have been detected in parts of northwestern Europe (Giuntoli *et al*., 2012; Hattermann *et al*., 2012; Petrow and Merz, 2009a), while a decrease in frequency was observed in the Pyrenees (Giuntoli *et al*., 2012; Renard *et al*., 2008). Flood discharges in the lower Yangtze region showed an upward trend in the last 40 years (Jiang *et al*., 2008; Zhang *et al*. 2009), and both upward and downward trends were identified in four basins in the northwestern Himalaya (Bhutiyani *et al*., 2008). In Australia, only 30% out of 491 gauge stations showed trends at the 10% significance level, with decreasing magnitudes in southern regions and increasing magnitudes in the northern regions (Ishak *et al*., 2010). In snow-melt dominated regions, there is no compelling evidence of widespread change in flood magnitude in Arctic rivers (Shiklomanov *et al*., 2007) or in Nordic rivers (Wilson *et al*., 2010). Cunderlik and Ouarda (2009) reported significant trends, most of them decreases, in snowmelt-flood magnitudes at almost one fifth of 160 stations. Similar decreases were found for spring and annual maximum flows (Burn *et al*., 2010).

Attribution has been addressed by Hattermann *et al*. (2012), who identified parallel trends in precipitation extremes and flooding in Germany, which for the increasing winter floods are explained in terms of increasing frequency and persistence of circulation patterns favourable to flooding (Petrow *et al*., 2009b). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min *et al.*, 2011; see also Section 3.2.1).

There is *high confidence* that socio-economic losses from flooding are increasing, although attribution of the losses to anthropogenic climate change is seldom established (Handmer *et al*., 2012; Kundzewicz *et al*., 2013). Attribution of losses is highly uncertain due to *limited evidence* (Bruce, 1999; Höppe and Grimm, 2009; Mills, 2005; Malmstadt *et al*., 2009; Schmidt *et al*., 2009). There is *high agreement*, but *medium evidence*, that greater exposure of people and assets, and societal factors is related to population and economic growth, contribute to the increased losses (Bouwer *et al*., 2007; Changnon, 2001; Pielke *et al*., 2005). Several studies normalize the loss records for changes in exposure and vulnerability (Bouwer, 2011). Most find no contribution of flooding trends to the trend in losses (Barredo, 2009; Benito and Machado, 2012; Hilker *et al*., 2009), although increased flood-related losses are found for China (Jiang *et al*., 2005) and Korea (Chang *et al*., 2009). However these studies, mostly at country level, do not take into account the regional diversity of trends seen in some long-term peak flow records (Section 3.2.3).

The definition of drought or local dryness (Seneviratne *et al.*, 2012; their Box 3-3) depends upon different perspectives (meteorological, hydrological, and agricultural), the variables considered relevant (precipitation, temperature, evapotranspiration, soil humidity) and the chosen index (e.g., Palmer drought severity index (PDSI), consecutive dry days (CDD), simulated soil moisture anomalies (SMA)).The AR4 (Trenberth *et al*., 2007) reported that the global extent of very dry areas (PDSI $\leq$ -3.0) more than doubled since the 1970s, and that droughts have increased since then particularly in the tropics and sub-tropics (Dai *et al*., 2004). There is substantial uncertainty in drought analyses based on indirect indexes such as the PDSI (Hartmann *et al*., 2013 (WGI Chapter 2); Dai, 2013; Sheffield *et al*., 2012). In a revised assessment using indices such as CDD and SMA rather than the simple PDSI, Seneviratne *et al.* (2012) found that some regions of the world, notably southern Europe and west Africa, have experienced trends toward more intense and longer droughts, while others (e.g. Central North America and Northwestern Australia) exhibited opposite trends (*medium confidence*). They attributed these patterns to anthropogenic influence on precipitation and temperature (*medium confidence*), although with *low confidence* for single regions.

Regarding vulnerability, some studies detect large supply-side reductions due to climate change that may stress existing water systems (Vanham *et al*., 2009), and others show how small reductions can be managed by existing supply systems or by moderate increases in adaptive capacity (Li *et al*., 2010).

3.3. Drivers of Change for Freshwater Resources

3.3.1. Climatic Drivers

Precipitation and potential evaporation are the main climatic drivers controlling freshwater resources. Precipitation is strongly related to the water-vapor content or specific humidity of the atmosphere, because saturation specific humidity depends on temperature: warmer air can hold much more water vapor. Temperature has increased in recent decades while surface and tropospheric relative humidity (the ratio of specific humidity to saturation specific humidity) have changed little (Hartmann *et al*., 2013 (WGI Chapter 2)). This need not imply either more precipitation or more actual evaporation, although commonly both do increase. Among other climatic drivers are atmospheric carbon dioxide (Section 3.2.3) and deposited black carbon and dust (Box 3-1 in Section 3.4.4). Both of the latter, in even very small concentrations, enhance melting of snow and ice markedly by reducing the surface albedo.

The evolution of the climatic drivers is uncertain mainly because of: (1) internal variability of the atmospheric system; (2) inaccurate modelling of the atmospheric response to external forcings (for example anthropogenic greenhouse radiation, solar and volcanic influences, and changes of land use and land cover); and (3) the external forcing itself, as expressed in the range of outcomes from the chosen emissions scenarios. Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of CMIP5 projections (Figure 3-4). The contribution of internal variability diminishes progressively. By no later than mid-century, discrepancies between models account for most of the uncertainty in precipitation, but the uncertainty in temperature (Kirtman *et al.*, 2013 (WGI Chapter 11)) is due mostly to divergent scenarios, which never contribute more than one third to the uncertainty in 21st-century precipitation. Uncertainty due to downscaling of the output of climate models, and to the hydrological models themselves, is addressed in Section 3.4.1.

[INSERT FIGURE 3-4 HERE
Figure 3-4: Variance in projections of changes in decadal-mean precipitation for boreal summer (June, July, and August), decomposed into contributions from three sources of uncertainty. Simulations were for 2000-2100 under the SRES A1B, A2 and B1 scenarios, with one ensemble member taken from each of 14 CMIP3 GCM experiments. From Hawkins and Sutton (2011).]

CMIP5 simulations of the water cycle during the 21st century, with constraints from 20th-century observations, can be summarized as follows (Collins *et al*., 2013 (WGI Chapter 12)):

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases by about 1.5 times more over land than over ocean (*very high confidence*).
- Warming is greatest over the Arctic (*very high confidence*), implying zonally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and the extent and duration of snow cover decrease (*high confidence*). In the coldest regions, however, increased specific humidity due to warming means that increased winter snowfall outweighs increased summer snowmelt.
- Wet regions become wetter and dry regions become drier (*medium confidence*), although one observational analysis (Sun *et al.*, 2012) is discordant; moreover the models tend to underestimate observed trends in precipitation (Noake *et al.*, 2012) and its observed sensitivity to temperature (Liu *et al.*, 2012).
- Precipitation tends to increase in equatorial, middle and high latitudes and to decrease in subtropical latitudes (*medium to high confidence*), and global average precipitation increases (e.g. Collins *et al*., 2013 (WGI Chapter 12), their Figure 12-41). Precipitation changes become statistically significant only when temperature rises by at least 1.1-1.4°C (Mahlstein *et al.*, 2012). In many regions, projected 21st-century changes lie within the range of late-20th-century natural variability.
- Models consistently project decreases of precipitation in the Mediterranean, Mexico and central America, and parts of Australia, and increases in India and north and central Asia (*high confidence*).
- Evaporation increases almost everywhere, especially at higher northern latitudes and generally in concert with precipitation (Collins *et al*., 2012 (WGI Chapter 12), their Figure 12-25). This leads to decreases of soil moisture in many regions, particularly central and southern Europe, southern North America and southern Africa (*medium confidence*; Collins *et al*., 2013 (WGI Chapter 12), their Figure 12-23).

More intense extreme precipitation events are expected (IPCC, 2012). Among proposed reasons, one is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to "empty" the atmospheric column (Utsumi *et al.*, 2011; Berg *et al.*, 2013). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986-2005 are projected to have return periods in 2081-2100 that are shorter in proportion to the intensity of forcing: about 15 (RCP(representative concentration pathway)2.6), 11 (RCP4.5) and 6 (RCP8.5) years (Kharin *et al.*, 2013). Unlike annual mean precipitation, for which the simulated sensitivity to warming is typically 1.5-2.5 % K^{-1}, the 20-year return amount of daily precipitation typically increases at 5-9 % K^{-1}. Agreement between GCM-simulated extremes and reanalysis extremes is good in the extra-tropics but poor in the tropics, where there is *robust evidence* of greater sensitivity (10±4 % K^{-1}; O'Gorman, 2012). In spite of the intrinsic uncertainty of sampling infrequent events, variation between GCMs is the dominant contributor to uncertainty.

GCM-simulated changes in the incidence of meteorological droughts vary widely, so that there is at best *medium confidence* in projections (Seneviratne *et al.*, 2012). Regions where droughts are projected to become longer and more frequent include the Mediterranean, central Europe, central North America and southern Africa.

3.3.2. Non-Climatic Drivers

In addition to climate change, the future of freshwater systems will strongly be impacted by demographic, socio-economic and technological changes, including lifestyle changes. Given the large uncertainty of climate models in translating emissions scenarios into projections of climatic change, a wide range of possible future development of non-climatic drivers is compatible with a wide range of climate change (Moss *et al*., 2010) particularly in terms of the number of population under high water stress (Kiguchi *et al*., 2013). This means that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic and ecological conditions, and thus may lead to very different impacts and vulnerabilities (Section 3.5). Therefore, the five shared socioeconomic pathways (SSP) socio-economic scenarios, which include narratives and quantifications of population and economic development (IIASA, 2012), can be combined with more than one GHG emissions scenario (representative concentration pathway (RCP)) (Moss *et al*., 2010).

Of particular importance for freshwater systems is the future agricultural land use, and in particular irrigation, as irrigation accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009). Due to mainly population and economic growth but also due to climate change, irrigation may significantly increase in the future. The share of irrigation from groundwater is expected to increase due to increased variability of surface water supply (Taylor *et al*., 2012a).

3.4. Projected Hydrological Changes

Generally, hydrological changes are evaluated by comparing possible future hydrological conditions to historical conditions. These projected changes are helpful indicators for understanding human impact on nature and for supporting adaptation to climate change. However, for supporting decisions on climate mitigation, it is more helpful to compare hydrological changes that may occur under different future GHG emissions scenarios. Examples of studies that assess hydrological changes and water-related impacts of climate change under different emissions or global warming scenarios are compiled in Table 3-2. They illustrate the benefits of reducing GHG emissions for the Earth's freshwater systems.

[INSERT TABLE 3-2 HERE
Table 3-2: Hydrological changes and freshwater-related impacts of climate change on humans and ecosystems that could be reduced with lower GHG emissions.]

3.4.1. Methodological Developments in Hydrological Impact Assessment

Since the AR4 many assessments of the potential impact of climate change on hydrological characteristics have been published. Most have applied a now-standard methodology to estimate impacts, using information from climate models to perturb a baseline weather record and a hydrological model to simulate river flows, recharge or water quality (see Section 3.6.3 for methods to estimate impacts specifically for water management purposes).

Most climate change impact assessments have been based on the use of a small number (five or fewer) of climate scenarios. An increasing number has used larger ensembles from the AR4 CMIP3 scenario set (Arnell, 2011b; Arnell and Gosling, 2013a; Bae *et al*., 2011; Chiew *et al*., 2009; Gosling *et al*., 2010; Jackson *et al*., 2011) or ensembles of regional and global climate models (Kling *et al*., 2012; Olsson *et al*., 2011). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections (see Section 3.6.3) and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke *et al*., 2009b; Christierson *et al*., 2012; Manning *et al*., 2009). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered.

Most assessments have used a hydrological model with the 'delta-method' to create scenarios, applying projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator; several such downscaling methods have been developed (Fowler *et al*., 2007a). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data (Chen *et al*., 2011; Quitana Segui *et al*., 2010), and the range in projected change between downscaling approaches can be as large as the range between different climate models. An increasing number of studies (Fowler and Kilsby, 2007b; Kling *et al*., 2012; Veijalainen *et al*., 2012) have run models with input data produced by bias-correcting regional or global climate model data (Piani *et al*., 2010; van Pelt *et al*., 2009; Yang *et al*., 2010); unlike the delta method, this means that the simulated future weather incorporates changes in variability as projected by the regional model. On the contrary, the delta method only can reflect the projected changes of the mean state and cannot reflect the changes in variability, and various methodologies are proposed and their characterstics are compared. The choice of bias-correction method can cause discrepancy in the results as a choice of emission scenario or GCM (Watanabe *et al*., 2012). A few studies (e.g. Falloon and Betts, 2006; 2010; Hirabayashi *et al*., 2008) have examined river runoff as simulated directly by a high-resolution climate model; because no bias-correction is applied, the pattern of variability in absolute simulated runoff across space is driven by the simulated precipitation, although the simulated change in runoff should be more consistent with the changes as simulated using a hydrological model off-line. However, this has not yet been systematically evaluated.

The effects of hydrological model parameter uncertainty are typically small when compared with the range from a large number of climate scenarios, but can be substantial when only a small number of climate scenarios are used (Arnell, 2011b; Cloke *et al*., 2010; Lawrence and Haddeland, 2011; Steele-Dunne *et al*., 2008; Teng *et al*., 2012; Vaze *et al*., 2010). However, several new studies suggest that the effects of model structural uncertainty can be substantial (Dankers *et al*., 2013; Davie *et al*., 2013; Haddeland *et al*., 2011; Hagemann *et al*., 2012; Schewe *et al*., 2013), due primarily to different representations of evaporation and snowmelt processes. Two global-scale multi-model studies on projected mean annual river runoff or discharge used the output of three (five) GCMs to drive eight (eleven) global hydrological models (Hagemann *et al*., 2012; Schewe *et al*., submitted). It was found that that hydrological and climate models contribute to the overall uncertainty of projected changes of runoff (discharge) water flows to similar extents globally, with distinct spatial patterns of dominance. The uncertainty of projected actual evapotranspiration, however, was determined to be dominated by the hydrological models.

The vast majority of published impact assessments have followed the conventional scenario-driven approach. Other approaches are, however, feasible. Cunderlik and Simonovic (2007) developed an inverse technique, which starts by identifying critical hydrological changes, uses a hydrological model to determine the meteorological conditions which trigger those changes, and then interprets climate model output (via a weather generator) to identify the chance of these meteorological conditions occuring in the future; Fujihara *et al*. (2008a; 2008b) applied the technique in a catchment in Turkey. The advantage of this approach is that it is not necessary to use the hydrological model to simulate future hydrological characteristics. Another scenario-independent approach constructs response

surfaces relating sensitivity of a hydrological indicator to changes in climate. Several studies have used a water-energy balance framework (based on Budyko's hypothesis and formula) to characterise the sensitivity of average annual runoff to changes in precipitation and evaporation (Donohue *et al*., 2011; Renner and Bernhofer, 2012a; Renner *et al.*, 2012b). Prudhomme *et al*. (2010) constructed a response surface showing change in flood magnitudes by running a hydrological model with systematically-varying changes in climate. Not only does this approach show sensitivity of a system to change, it also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration

Based on global and regional climate models as well as physical principles, it is projected that global evapotranspiration is very likely to increase in a warmer climate resulting in an acceleration of the hydrologic cycle (Collins *et al*., 2013 (WGI Chapter 12)). Many uncertainties in both magnitude and direction of long-term trends are apparent. Evapotranspiration is not only affected by rising temperatures but also by changing radiation, changes in soil water content, decreases in bulk canopy conductance associated with rising CO_2 concentrations and climate change related vegetation changes (Box CC-VW; Katul and Novick, 2009).

An important source of uncertainty in hydrological projections is the response of empirically estimated potential evapotranspiration (PET) to climate change. Kingston *et al*. (2009) using six different methodologies suggest an increase in PET associated with a warming climate. Ekström *et al*. (2007) found that the Blaney-Criddle formulation lead to smaller changes than the Penman-Monteith formula. However, differences in the PET climate change signal of over 100% are found between the methods, with an uncertainty of 20% to 40% to the observed baseline period (1961-1990).

3.4.3. Soil Moisture and Permafrost

Potential evaporation, which would reduce soil moisture, is projected to increase particularly in southern Europe and Central America, Southern Africa and Siberia (Seneviratne *et al.*, 2010). Lower soil moisture increases the risk of extreme hot days (Hirschi *et al.*, 2011; Seneviratne *et al.*, 2006) and heat waves. For a range of scenarios, low soil moisture episodes of 3-6 month duration double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20th century and the end of the 21st century. This is particularly the case where reductions in soil moisture are projected (Sheffield and Wood, 2008). Strong natural variability in drought occurrence and intensity makes the generally monotonic increases statistically not different from current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost ofnorthern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (see Figure 4-18 in Chapter 4). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, permafrost area is projected to stabilize at near 20% below the 20th century area, and then begin to increase slightly.

3.4.4. Glaciers

All projections for the 21st century (Church *et al*., 2013) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer, not spring as in snow-covered catchments. As the glaciers shrink, their relative contribution decreases and the annual runoff peak shifts towards spring (e.g., Huss, 2011). This shift is expected with *very high confidence* as an impact of warming. The relative importance of high-summer glacier meltwater can be substantial, for example 25% of August discharge in basins draining the European Alps, with area 10^5 km^2 and only 1% glacier cover; high-summer water supply will therefore be reduced noticeably by the projected glacier shrinkage (based on regional scenarios derived from the SRES A2 and B2 scenarios) to only 12% of 2008 extent by 2100 (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig *et al*., 2007).

If warming proceeds at a constant rate then if, as expected, melting of stored glacier ice per unit area increases and total glacierized area decreases, the total water yield passes through a maximum: "peak meltwater". Peak-meltwater dates have been projected between 2010 and 2050 (different regions of China; Xie *et al.*, 2006); 2010-2040 (European Alps; Huss, 2011); and 2060-2080 (the world; Radić and Hock, 2011). Pending further regional-scale investigations, there is *medium confidence* that the peak response to 21st-century warming will fall within the century in most inhabited glacierized regions, where at present society is benefitting from a transitory "meltwater dividend". Variable climatic forcing leads to complex variations of both the melting rate and the extent of glacier ice, which depend on each other. Peak meltwater can therefore be difficult to identify, but it has been detected with *medium confidence* in some studies (Table 3-1).

If they are in long-term equilibrium, glaciers reduce the interannual variability of water resources by storing water during cold or wet years and releasing it during warm years (Viviroli *et al.*, 2011). As glaciers shrink, however, their diminishing influence may make the water supply less dependable.

_____ START BOX 3-1 HERE _____

Box 3-1. Case Study: Himalayan Glaciers

Like glaciers elsewhere (Comiso *et al*., 2013 (WGI Chapter 4); their FAQ 4.1), Himalayan glaciers are losing mass. They are therefore of growing concern because they are important resources of freshwater for their host countries (Bhutan, China, India, Nepal and Pakistan). The total resource of ice is known only roughly; estimates range from 2100 to 5800 Gt (Bolch *et al*., 2012).

Himalayan glacier mass budgets have been negative on average for the past five decades. The loss rate may have become greater after about 1995, but it has not been greater in the Himalaya than elsewhere (Figure 3-5). A recent large-scale measurement, highlighted in the figure, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements are not representative of the regional average. Thus Figure 3-5 also illustrates the uncertainty of generalizations from sparse data.

[INSERT FIGURE 3-5 HERE
Figure 3-5: A compilation of all published glacier mass balance measurements from the Himalaya (based on Bolch *et al*., 2012). Each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements). Region-wide measurement (Kääb *et al*., 2012) was by satellite laser altimetry. Global average (Comiso *et al*., 2013 (WGI Chapter 4)) is shown as a 1-sigma confidence region.]

Radić *et al*. (2013) projected glacier mass changes for 2006-2100 by simulating the response of a glacier model (Radić and Hock, 2011) to CMIP5 projections from 14 GCMs under scenario RCP4.5. Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15-78%. The model-mean loss to 2100 is 45% under RCP 4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier suggestion of complete disappearance by 2035 (Cruz *et al*., 2007). At the catchment scale, however, 21st-century projections do not yet present a coherent region-wide picture.

For an imposed warming rate of 0.06 K/year, simulated peak meltwater discharge was reached in hypothetical glacierized basins around 2050 in the drier western Himalaya and around 2070 in the wetter eastern Himalaya (Rees and Collins, 2006). The GCM-forced simulations of Immerzeel *et al*. (2012) in eastern Nepal, in contrast, show runoff increasing throughout the century because increased precipitation over-compensates for the loss of ice; because the monsoon and the melt season coincide here, there is no seasonal shift of peak discharge.

The growing atmospheric burden of anthropogenic black carbon implies reduced glacier albedo, and measurements in eastern Nepal (Yasunari *et al*., 2010) suggest that this could yield 70-200 mm/year of additional meltwater. In global terms, the Himalaya and southern Tibet are a hotspot for deposition of soot, which may outweigh the greenhouse effect as a radiative forcing agent for snowmelt (Qian *et al*., 2011).

Moraine-dammed ice-marginal lakes continue to cause concern (Fujita *et al*., 2009). In the western Himalaya, they are small and stable in size, while in Nepal and Bhutan they are more numerous and larger, and most are growing (Gardelle *et al*., 2011). Thus the hazard has increased, but there has been little progress on the predictability of dam failure.

Himalayan glacier meltwater is an increasing, and during this century is expected to become a decreasing, component of a complex mix of sources of freshwater. Its relative contribution to water resources decreases with distance downstream, being greatest where it enters seasonally arid regions such as the lower Indus, and becoming negligible in the monsoon-dominated Ganges-Brahmaputra (Kaser *et al*., 2010). In the mountains, however, both dependence on and vulnerability to glacier meltwater can be of serious practical concern when measured per head of population.

_____ END BOX 3-1 HERE _____

3.4.5. Runoff and Stream Flow

Since the publication of the AR4 there have been very many catchment-scale studies of the potential impacts of climate change on runoff and streamflow, and many of the spatial gaps identified in AR4 have been plugged to a very large extent. Virtually all of these studies have estimated impacts using scenarios constructed from climate models. The projected impacts in a catchment depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change in the magnitude and seasonal distribution of precipitation, temperature and evaporation. Catchment sensitivity is largely a function of the ratio of runoff to precipitation; sensitivity is greater the smaller the ratio. Figure 3-6 shows projected change in mean monthly runoff for seven catchments across the globe, using the same seven climate model patterns scaled to represent an increase in global mean temperature of 2^{o}C above the 1961-1990 mean (Arnell, 2011b; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*, 2011; Nobrega *et al*, 2011; Thorne, 2011a; Xu *et al*., 2011); changes under the HadCM3 model with 2 and 4^{o}C increases are highlighted. The figure illustrates how the same climate model has a different effect in different catchments, shows considerable variability in estimated impact in each catchment across the seven scenarios and also show non-linear response to increasing forcing (in the Mitano catchment). The uncertainty is largely driven by differences in projected changes in precipitation between different climate models. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

[INSERT FIGURE 3-6 HERE
Figure 3-6: Range in change in mean monthly runoff across seven climate models in seven catchments, with a 2^{o}C increase in global mean temperature (above 1961-1990) (Arnell, 2011b; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011a; Xu *et al*., 2011). Changes with the HadCM3 climate model with increases of 2 and 4^{o}C are highlighed.]

A number of studies have used projected changes in runoff and streamflow across the global domain (e.g. Arnell and Gosling, 2013a; Döll and Zhang, 2010; Fung *et al*., 2011; Gosling *et al*., 2010; Schewe *et al*., 2013), and some assessments have used directly the output from global climate models (Hirabayashi *et al*., 2008; Okazaki *et al*., 2012; Tang and Lettenmaier, 2012). (Figure 3-7). Most of these studies have used CMIP3 climate models, although a small number (Okazaki *et al*., 2012; Schewe *et al*., 2013) have used CMIP5 models. The projected changes are dependent on the climate scenarios used, but it is possible to identify a number of consistent patterns. Average annual runoff is projected to increase at high latitudes and in the wet tropics, to decrease in most dry tropical regions. However, there are some regions where there is very considerable uncertainty in the magnitude and direction of change, specifically south Asia and large parts of South America.Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation, with uncertainty in projected changes in rainfall across South Asia being particularly significant. [Cross reference to WG1 to be included here]. Changes in average annual runoff are typically between 1 and 3 times as large as changes in average annual precipitation (Tang and Lettenmaier, 2012).

[INSERT FIGURE 3-7 HERE
Figure 3-7: Relative change in annual discharge at 2°C (2.7°C above pre-industrial) compared to present-day, under RCP8.5. Color hues show the multi-model mean change, and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign). (Schewe *et al*., 2013)]

There is a much more consistent pattern of future change in the timing of streamflows in areas with regimes currently influenced by snowfall and snowmelt. A global analysis (Adam *et al*., 2009) with multiple climate scenarios shows a consistent shift to earlier peak flows, except in some regions areas where increases in precipitation are sufficient to result in increased, rather than decreased snow accumulation during winter. The greatest changes are found near the boundaries of regions which currently experience considerable snowfall, where the marginal effect on snowfall and snowmelt of higher temperatures is greatest.

3.4.6. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of relevant studies and review papers (Green *et al*., 2011; Taylor *et al*., 2012a) has since then increased significantly. Ensemble studies of the impact of climate change on groundwater recharge and partially also groundwater levels were done for the globe (Portmann *et al*., 2013), all of Australia (Crosbie *et al*., 2012), the German Danube basin (Barthel *et al*., 2010), and aquifers in temperate Belgium and England (Goderniaux *et al*., 2011; Jackson *et al*., 2011), the Pacific coast of the USA and Canada (Allen *et al*., 2010) and for a study site in the semi-arid part of the USA (Ng *et al*., 2010). The number of applied climate models ranged from 4 to 20, and with two exceptions, only one emissions scenario, mostly SRES A2, was taken into account. Due to the uncertainty of climate models, the range of future groundwater changes was large, from significant decreases to significant increases for the individual study areas, and the range of percent changes of projected groundwater recharge mostly exceed the range of projected precipitation changes.

When considering a particular climate scenario, land areas where total runoff are projected to increase (or decrease) roughly coincide with the areas where groundwater recharge and thus renewable groundwater resources are projected to increase (or decrease) (Kundzewicz and Döll, 2009). Changes in precipitation intensity affect groundwater recharge as a fraction of total runoff. Increased precipitation intensity, for example, may decrease groundwater recharge due to exceedance of infiltration capacity (typically in humid areas) or increase it due to a fast percolation through the root zone from where water otherwise would be evapotranspired (typically in semi-arid areas) (Taylor *et al*., 2012b; Liu, 2011). The response of groundwater recharge and levels to climate change is small in case of fine-grained soils and clayey confining layers, and large in case of sandy soils and water table aquifers (van Roosmalen *et al*., 2007). It also depends on the vegetation, in particular as vegetation adapts to climate change and thus modifies the groundwater response to climate change (Box CC-VW).

Decreasing snowfall may lead to lower groundwater recharge even if precipitation remains constant; at sites in the Southwestern USA, snowmelt provides at least 40-70% of groundwater recharge, although only 25-50% of average annual precipitation falls as snow (Earman *et al*., 2006). Due to expected increases in precipitation and streamflow variabililty, climate change is also expected to lead to increased groundwater abstractions (Taylor *et al*., 2012a), lowering groundwater levels and storages.

Coastal groundwater is affected by climate change not only due to changes in groundwater recharge but also due to sea level rise which, together with the rate of groundwater pumping, determines the location of the saltwater/freshwater interface. While most confined aquifers are expected to be unaffected by sea level rise, most unconfined (water table) aquifers are *likely* to suffer from saltwater intrusion and a loss of freshwater volume (Werner *et al*., 2012; Masterson and Garabedian, 2007). Assuming an average salt water density of 1.025 g/cm^3, the thickness of the unconfined freshwater layer decreases by roughly 40 meters if difference between the fresh groundwater table and the sea level is decreased by 1 meter due to either sea level rise or decreased groundwater recharge (Werner *et al*., 2012). Salt water intrusion is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011).

Water table aquifers of flat (coral) islands and delta regions are expected to suffer very strongly from saltwater intrusion due to sea level rise or potentially decreasing groundwater recharge. The latter is also affected by storm surges, with increased upstream transport of saline waters in the rivers which then contaminate the underlying fresh groundwater from above (Masterson and Garabedian, 2007). Even small rates of groundwater pumping near the coast are expected to lead to stronger salinization of the coastal groundwater than sea-level rise during the 21st century (Ferguson and Gleeson, 2012).

Changes in groundwater recharge also affect streamflow in rivers. In a catchment of the Upper Nile basin in Uganda, mean global temperature increases of 4°C or more are projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010). Changing groundwater tables have an effect on land surface fluxes and thus the climate system which remains to be fully explored (Jiang *et al*., 2009). However, it has been shown that the effect to be strongest in case of semi-arid condition where the groundwater table is less than 7 meter below the ground (Ferguson and Maxwell, 2010).

3.4.7. Water Quality

The impact of climate change on the quality of water occurs through a complex set of natural and anthropogenic mechanisms working in parallel and in series and, occasionally, even at the same time. Projecting future conditions is a difficult task involving the integration of climate models outputs with those used to analyze the transportation and transformation of pollutants in water, soil, and air (Andersen *et al*., 2006; Arheimer *et al*., 2005; Bonte and Zwolsman, 2010; Ducharne, 2008; Marshall andRandhir, 2008; Rehana and Mujumdar, 2012; Towler *et al*., 2010; Trolle *et al*., 2011; Wilby *et al*., 2006). In addition, such models use different scales and have to be adapted and calibrated to local conditions; often a difficult task due to a lack of sufficient and appropriate information. As a result, there is little in the literature with regard to the future impacts of climate change on water quality, and this is available where the uncertainty is high.

From the projections reported (Figure 3-3), it is evident that results are highly dependent on (Bonte and Zwolsman, 2010; Chang, 2004; Kundzewicz and Krysanova, 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011; Whitehead *et al*., 2009a; 2009b) (a) local conditions; (b) climatic and environmental assumptions, such as other types or sources of pollution; and (c) current impacts (i.e., pollution state/reference state). Most projections are useful in affirming that observed impacts will be *likely* to prevail in the future for natural and artificial reservoirs (Bonte and Zwolsman, 2010; Brikowski, 2008; Ducharne, 2008; Loos *et al*., 2009; Marshall andRandhir 2008; Qin *et al*., 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011), rivers (Andersen *et al*., 2006; Bowes *et al*., 2012; Whitehead *et al*., 2009a; 2009b) and groundwater (Butscherand Huggenberger, 2009; Rozemeijer *et al*., 2009), and will be a result of the combination of the change and variations in air/water temperature and precipitation/storm runoff, combined with many other factors that also impact upon the quality of water (Chang, 2004; Whitehead *et al*., 2009a).

3.4.8. Soil Erosion and Sediment Load

Heavy rainfall events are *likely* to increase in the 21st century over many areas on the globe (Seneviratne *et al*., 2012), which may lead to a disproportionate amount of erosion relative to the total rainfall contribution. At global scale, changes in soil erosion in the 2090s compared to the 1980s is expected to increase about 14% (9% attributed to climate and 5% due to land use) with significant increase of 40-50% in Australia and Africa (Yang *et al*., 2003). The largest amounts are expected on erosion-prone semiarid areas where contribution of extreme events may constitute up to 40% of total erosion (Baartman *et al*., 2012). In agricultural lands of temperate regions, soil erosion may respond in complex non-linear ways; for instance in agricultural land on the UK South Downs a rainfall scenario of 10% increase in winter rainfall could give increases of annual erosion by up to 150%, that is be explained by the interaction of the timing of rainfall (winter) during the early growing season (Favis-Mortlock and Boardman, 1995). On the other hand, in central Europe (Austria) regional climate model HadRM3H (SRES A2, 2010-2099) projects a net-decrease of rainfall amount of 10-14% in erosion sensitive months giving rise to decline

in soil erosion in all tillage systems by 11-24% (Scholz *et al*., 2008). Land management practices are critical to reduce soil erosion under projected climate change. In the China's Loess Plateau, GCMs project a soil erosion increase of 5-195% during 2010-2039 under conventional tillage, whereas under conservation tillage shows decreases of 26-77% (Li *et al*., 2011).

Climate change is *likely* to affect sediment load in rivers through soil erosion processes, water discharge, and changes in land use and land cover. For example, an increase in water discharge of 11-14% in two Danish rivers was projected to raise the annual suspended sediment between 9% and 36% during the period 2071-2100 (Thodsen *et al*., 2008). Projected river's sediment flux in response to climate change needs also to consider the sensitivity of land cover to climate change. For instance, Gomez *et al*. (2009) simulated the changes in water flow and suspended sediment flux in the Waipaoa River in New Zealand showing that climate change may reduce the mean flow by 13% in the 2030s and 18% in the 2080s, producing changes of annual suspended sediment flux of ±1 Mt/year by the 2030s, but depending on the climate change scenario by the 2080s it may either decline by 1 Mt/year (under warmer drier conditions) or increase by 1.9±1.1 Mt/year (warmer but not substantially drier). Increases in total precipitation amount, along with melting glaciers, permafrost degradation, and the shift of precipitation patterns from snow to rainfall, will further increase soil erosion and sediment loads of the rivers which are currently fed mainly by glaciers (Lu *et al*., 2010). In a major headwater basin for the Ganges River, an increased precipitation and enhanced melting of glaciers will increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropical regions, the intensity of stronger storms from cyclones was projected to increase 2-11% by 2100 (Knutson *et al*., 2010).

In summary, projected increase in heavy rainfall and temperature changes are *very likely* to produce changes in soil erosion and sediment yield; however, overall there is a *low confidence* on the rate of these changes due to the non-linear response of soil erosion and its high dependence on land cover. There impacts of climate change in soil erosion is expected to double the one induced by land use change by 2090s (Yang *et al*., 2003), although management practices may mitigate the sediment yield at catchment scale.

3.4.9. Extreme Hydrological Events (Floods and Droughts)

The SREX report (IPCC, 2012) recognized that projected precipitation and temperature changes imply possible changes in floods, although overall there is *low confidence* in projections of changes in fluvial floods. Projected increases in heavy rainfall would contribute to increases in rain generating local flooding, in some catchments or regions (Kundzewicz, 2013; Seneviratne *et al*., 2012). The studies supporting these assessments relied on a single GCM, which was the major source of *limited evidence* and thus *low confidence* in SREX (IPCC, 2012). Recent literature on global flood projections are based on ensemble from global hydrology models couple with multiple CMIP5 GCM simulations (Dankers *et al*., 2013; Hirabayashi *et al*., 2013). These model experiments show that flood hazards are increasing in more than half of the globe with a great variability even at the scale of individual river basins. In general, these studies show consistent results with increasing flood hazards occurring in parts of South Asia, Southeast Asia, East Africa, Central and West Africa, Northeast Eurasia, and South America. In contrast, a decrease in flood frequency was projected in parts of North and East Europe, Anatolia, Central Asia, central North America, and southern South America (Figure 3-8). This overall pattern is considerably similar to what was described in SREX (IPCC, 2012) as a summary of limited global or continental scale studies where each study relied on a single or a limited number of climate models. Thus, the global/continental-scale flood projection has gained ground and confidence could become higher than SREX (IPCC, 2012). However, uncertainty is still large at the global and continental scales particularly about the magnitude of changes. At local scale, even the sign of the change do not necessarily agree among GCMs (Dankers *et al*., 2013; Hirabayashi *et al*., 2013).

[INSERT FIGURE 3-8 HERE
Figure 3-8: Results of flood hazard change for the 30-year return level of river flow (Q30) from ensemble of 5 CMIP5 GCM simulations under RCP8.5 coupled with nine global hydrology and land surface models (named as impact models (IMs)) that provided simulations of daily river discharge at a global 0.5-degree grid for two 30-year periods (1971-2000 and 2070-2090) (Dankers *et al*., 2013). Top: Number of experiments (out of 45 in total) showing an increase (top left) or decrease (top right) in the magnitude of Q30 of more than 10% in 2070-2099 under RCP8.5, compared to 1971-2000. Bottom left: Average change in the magnitude of Q30 across all experiments.

Bottom right: Ratio of GCM variance to IM variance. GCM variance was computed as the variance of the change in Q30 across all GCMs for each individual IM, and then averaged over the 9 IMs; IM variance was computed as the variance of the change in Q30 across all IMs for each individual GCM, and then averaged over the 9 GCMs. In dark green (purple) areas GCM (IM) variance predominates.]

Projections at the catchment and/or river-basin scale are also being carried out (e.g, Dobler *et al*., 2012; Kay and Jones, 2012; Rojas *et al*., 2012) in addition to examples referred to in SREX (IPCC, 2012) and AR4, although projections for developing countries and regions are still limited (e.g., Ghosh and Dutta, 2012; Hunukumbura and Tachikawa 2012; Khazaei *et al*., 2012) and they tend to rely on a single or a limited number of climate models.

SREX (IPCC, 2012) assessed the projection of drought as: There is *medium confidence* in a projected increase in duration and intensity of droughts in some regions of the world, including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Elsewhere there is overall *low confidence* because of insufficient agreement of projections of drought changes (dependent both on model and dryness index). Definitional issues and lack of data preclude *higher confidence* than *medium* in observations of drought changes, while these issues plus the inability of models to include all the factors *likely* to influence droughts preclude stronger *confidence* than *medium* in the projections. Note that the assessment of SREX (IPCC, 2012) is different to a certain degree from the one in AR4, in that confidence has become slightly lower, after carefully re-examining the AR4 assessment and adding post-AR4 studies.

Recently future changes in consecutive dry days (CDD) and simulated soil moisture anomalies (SMA) are calculated based on CMIP5 multi-model outputs, and compared CMIP5-based drought projections with CMIP3-based projections that were shown in SREX (Orlowsky and Seneviratne, 2012). It turns out that CMIP5-based projections are generally consistent with CMIP3-based projections except that drought at northeast Brazil is not clear by the SMA index obtained from CMIP5. Therefore, the above assessment on global-scale drought projection in SREX (IPCC, 2012) could remain almost the same here, even though definitional issues of drought remain yet to be solved.

3.5. Impacts, Vulnerabilities, and Risks

3.5.1. Availability of Water Resources

Approximately 80% of the world's population is currently exposed to high levels of threat to water security, in terms of a range of indicators including water availability , water demand and pollution (Vörösmarty *et al*., 2010). The greatest threats are across much of Europe, in south Asia, eastern and northeastern China, and parts of southern Africa and the eastern United States. Climate change has the potential to alter the availability of water and therefore threats to water security.

Global-scale analyses so far have concentrated on measures of resource availability rather than the multi-dimensional indices used in Vörösmarty *et al*. (2010). All have simulated future river flows or groundwater recharge using global-scale hydrological models. Some have assessed future availability based on runoff per capita (Arnell *et al*., 2011c; Arnell *et al*., 2013b; Fung *et al*., 2011; Gosling and Arnell, 2013; Hayashi *et al*., 2010; Schewe *et al*., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to runoff or recharge availability (Arnell *et al*., 2011c; Gosling and Arnell, 2013). Döll (2009) constructed a groundwater sensitivity index which combined water availability with dependence on groundwater and the Human Development Index (Figure 3-9). In a study with five climate models driving eleven global hydrological models, climate change was estimated to add, on average, about 40% to the global number of people living under extreme water shortage, for a global mean temperature rise of 2.7°C above pre-industrial (Schewe *et al*., 2013). Up to this temperature rise, each degree of global warming is projected to confront an additional 7% of the global population with a severe decrease in water resources of 20% (Schewe *et al*., 2013; Table 3-2). There are several key conclusions from this set of studies. First, the spatial distribution of the impacts of climate change on resource availability varies considerably with the climate model used to construct the climate change scenario, and particularly with the pattern of projected rainfall change (Arnell *et al*., 2011c; Döll, 2009; Portmann *et al*., 2013; Schewe *et al*., 2013). There is a strong degree of consistency in projections of reduced availability around the

Mediterranean and parts of southern Africa, but much greater variation in projected availability in South and East Asia. Second, some water-stressed areas see increased runoff in the future (Section 3.4.5), and therefore a reduction in exposure to water resources stress -varying with the spatial pattern of projected changes in rainfall. Third, over the next few decades and for increases in global mean temperature of less than around 2°C above pre-industrial, changes in population will generally have a greater effect on changes in resource availability, relative to the present day, than climate change (Fung *et al*., 2011). Climate change would, however, regionally exacerbate or offset population pressures. Fourth, estimates of future water availability are sensitive not only to projections of future climate change and population assumptions, but also to hydrological impact model (Schewe *et al*., 2013) and the specific measure of stress or scarcity used.

[INSERT FIGURE 3-9 HERE
Figure 3-9: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios in which lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percent decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10%, as compared to the climate normal 1961-90 (Döll, 2009).]

Under climate change, reliable surface water supply is *likely* to decrease due to increased temporal variations of river flow that are caused by increased precipitation variability and decreased snow/ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and increase groundwater withdrawals (Kundzewicz and Döll, 2009). However, this option is only sustainable where groundwater withdrawals remain well below groundwater recharge. Groundwater is *not likely* to ease freshwater stress in those areas where climate change is projected to decrease groundwater recharge and thus renewable groundwater resources (Kundzewicz and Döll, 2009). The percentage of projected global population (SSP2 population scenario) that will suffer from a decrease of renewable groundwater resources GWR of more than 10% by the 2080s as compared to 1971-2000 was computed to range from 24% (mean based on 5 GCMs, range 11-39%) for RCP2.6 to 38% (range 27-50%) for RCP8.5 (Portmann *et al*., 2013; Table 3-2). Considering change of GWR as a function of mean global temperature (GMT) rise, the land areas affected by GWR decreases of more than 30% and 70% increase linearly with GMT between 0°C and 3°C. For each degree of GMT rise, an additional 4% of the global land area is cprojected to suffer from a GWR decrease of more than 30%, and an additional 1% to s a decrease of more than 70% (Portmann *et al*., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

Higher temperatures and increased variability of precipitation would, in general, lead to increased irrigation water demand, even if the total precipitation during the growing season remains the same (Bates *et al.*, 2008). Crop transpiration and therefore irrigation water requirements are *likely* affected by physiological and structural crop responses to increased atmospheric CO_2 concentration (Box CC-VW). Using 19 climate models to drive a global vegetation and hydrology, it was projected that global irrigation water requirement on areas presently equipped for irrigation would decrease by on average by 17% by the 2080s (if not limited by poor soils and nutrient availability), while it would remain approximately constant if CO_2 effects were not taken into account (Konzmann *et al.*, 2013). Even with the maximum CO_2-effect, increases of more than 20% are projected for Southern Europe and parts of China, the USA, Russia and Chile (Box CC-VW).

Irrigating crops can influence regional climate considerable. Irrigation is used to produce over 40% of the world's food, this is why irrigation is a one of the key elemements for food security in the future.

Effects of global irrigation on the near surface climate
It has been found (Sacks *et al*., 2009) that irrigation alters climate for instance by indirect effects like an increase in cloud cover. This effect can be significant in some regions, for example: cooling central and southern US, China,

and parts of Asia, in contrast, it warmed Canada by about 1 C°. Nevertheless, the impact is only at a regional level, as agriculture has little impact on the global mean temperatures. Precipitation increase occurs primarily downwind of the major irrigation areas, although precipitation in part of India decreases due to weaker summer (Puma and Cook, 2010).

Irrigation as adaptation strategy

Farmers could optimize production by adapting their use of fertilizers, pesticides and irrigation water to change climatic, political and economic conditions. To manage increasing yield variability and potential decrease in yield levels, irrigation constitutes an additional adaptation option which farmers might use (Finger *et al*., 2011).

About 4% of Sub-Saharan Africa arable land is irrigated. Irrigated land yields are up to five times that of rain fed areas. However, it must be the case that the costs of irrigation (e.g., capital, administrative, political) are high enough to balance or offset the benefits, thus and evaluation should be made considering local conditions (World Bank, 2009).

A study quantifying global changes in irrigation requirements on areas presently equipped for irrigation of major crop types has been realized indicating results from 19 GCMs for the year 2080. It was found a decrease in global irrigation of about 17% in the ensemble median. Additionally, an increase of more than 20% is projected with (*high likelihood*) for some regions such as South Europe and (*lower likelihood*) in Asia and North America.

Shifts in sowing dates constitute an adaptation option, for insance for maize production in Switzerland (World Bank, 2009), but sometimes this have to be combined with irrigation (Meza *et al*., 2009).

Complementary between mitigation and adaptation

A comparison of optimal input levels of nitrogen between rainfed and irrigated farming system shows different adaptation strategies. In rainfed production systems, reduced summer rainfalls lead to a reduction of the optimal production intensity for current and future scenarios. On the contrary, an increased application of nitrogen (i.e., a more intensive production) is an optimal response to climate change if irrigation is available. The difference in yield levels and yield variability between irrigated and rainfed farming systems will be higher with more marked climatic conditions (Finger *et al*., 2011).

3.5.2.2. Energy Production

Large amounts of water are required to produce energy by thermal power plants, hydropower and irrigated bioenergy crops (see Box CC-WE). Therefore, hydrological changes (Section 3.4) are expected to affect energy production, while changes in energy production due to climate change mitigation efforts will alter freshwater systems (Section 3.7.2.1), e.g. water availability for freshwater ecosystems (Section 3.5.2.4).

Hydropower generation is affected by changes in the mean annual river discharge, seasonal flows and daily flow variability as well as increased evaporation from reservoirs and changes in sediment fluxes. Projections of future hydropower generation in the Pacific Northwest of the USA are uncertain mainly due to the uncertainty of projected precipitation (Markoff and Cullen, 2008). Hydropower generation of Lake Nasser (Egypt) was computed to remain constant until the 2050s (based on an ensemble of 11 GCMs) but to decrease, on average (ensemble mean), to 90% of current mean annual production for the A2 (B1) emissions scenario, following the downward trend of mean annual river discharge (Beyene *et al*., 2010; Table 3-2). In snow-dominated basins, increased discharge in winter and lower and earlier spring floods have already been observed (Section 3.2.5) and the trend is *very likely* to continue in the future. This makes the annual hydrograph more similar to seasonal variations in electricity demand, providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Renofalt *et al*., 2010; for Sweden). In general, climate change requires adaptation of operating rules (Minville *et al*., 2009; Raje and Mujumdar, 2010) which may, however, be restricted by reservoir storage capacity. In California, for example, high-elevation hydropower systems with small storage, which rely on the storage capacity of the snowpack, are projected to suffer from decreased hydropower generation and revenues due to the increased occurrence of spills, unless

precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be costed effective (Madani and Lund, 2010).

Regarding water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, caused by increased stream temperatures and occurrence of low flows (van Vliet *et al*., 2012; Flörke *et al*., 2012). Lower emissions also lead to less severe impacts of climate change (Table 3-2). Economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are discussed in Chapter 10.

3.5.2.3. Municipal Services

Under anthropogenically altered climate conditions, water utilities are confronted by the following (Bates *et al*., 2008; Black and King, 2009; Bonte and Zwolsman, 2010; Brooks *et al*., 2009; Chakraborti *et al*., 2011; Christierson *et al*., 2012; Hall and Murphy, 2010; Jiménez, 2008a; Major *et al*., 2011; Mukhopadhyay and Dutta, 2010; Qin *et al*., 2010; Thorne and Fenner, 2011b; van Vliet and Zwolsman, 2008; Whitehead *et al*., 2009):

- Higher ambient temperatures is very likely to reduce snowpacks and glaciers, also they are very likely to increase the evaporation rate in lakes, reservoirs and aquifers. Both impacts is very likely to reduce the amount of water naturally stored reducing its availability. At the same time higher ambient temperatures is likely to increase the demand for municipal water as for many other uses. The overall situation resulting in a higher competition for water from different users.
- Shifts in river flows and the occurrence of droughts are likely to increase the need for artificial storage capacity.
- Higher water temperatures which exacerbate algal blooms in surface water potentially demanding for cyanotoxins control. Also a warmer environment potentially leads to changes in the quantity and quality of natural organic matter in water sources that are at the origin of disinfection by-products in chlorinated water. These issues contrast with potential increases in the efficiency of biological water and wastewater treatement processes resulting from increased water temperatures (Tchobanoglous *et al*., 2003).
- Drier conditions, resulting in a higher concentration of pollutants due to a reduction in dilution capacity. For groundwater sources, some pollutants of natural origin, including arsenic, iron, manganese and flurorides are likely to be an additional source of concern in areas already affected from, South East Asia (India), North and Latin America and Africa (Black and King, 2009).
- Elevated storm runoff, leading to higher loads of pathogens, nutrients and turbidity in water bodies from point and non-point sources of pollution. The indicators traditionally used to assess faecal pollution (faecal bacteria), as a result, is likely to be insufficient to track pathogens.
- Sea level rise, leading to increased salinity in aquifers in particular where groundwater recharge is very likely to decrease.

Water supply

With respect to the safe supply of water, many treatment plants are not designed to handle extreme influent variations that occur under climate variable conditions. These demand additional or even different infrastructure for treatment during periods of one to up to several months per year. In order merely to control the increased turbidity that would be *likely* to interfer with the disinfection process, higher coagulant doses would be needed, greater volumes of sludge would then be produced and need to be disposed increasing treatment costs (Zwolsman *et al*., 2010; Arnel *et al*., 2011). Depending on the extent of the impacts and local conditions resulting costs may or not be affordable.

Sanitation service

With regard to sewers, three climatic conditions are of interest from the perspectives of design and operation (NACWA, 2009; Zwolsman *et al*., 2010):

- Wet weather conditions -Heavy rainstorms challenge the existing capacity of sewerage systems due to the need to deal with increased amounts of pluvial water and even wastewater in combined systems, even for short periods of time. The current design, based on critical “design storms” defined through analysis of historical precipitation data, must be modified to include future scenarios. In addition new strategies to

prevent urban floods have to be developed considering not only the future climate but also many other factors such as urban design, land use, the "heat island effect" and topography (Chagnon, 1969).

- Sea level rise -The intrusion of brackish or salty water to sewers necessitates not only additional capacity of wastewater treatment but also processes that are able to operate with more saline wastewater.
- Dry weather conditions -During dry conditions, soil shrink as they lose humidity, eventually causing the cracking of water mains and sewers and with this the infiltration and exfiltration of water/wastewater. The combined effects of higher temperatures, increased concentrations of pollutants, longer retention times, and solids sedimentation may lead to increasing corrosion of sewers, shortening asset life and increasing maintenance costs. This is also likely to cause problems of septicity, higher pollutant contents and increased "first flush" concentrations.

Cities suffering from increased storm runoff are likely to experience the need to treat combined sewer overflows (CSO), due to increased amounts and varieties of pathogens and pollutants. Under drier conditions a high content of pollutants in wastewater, of any type, is to be expected and has to be dealt with (Whitehead *et al*., 2009a; 2009b; Zwolsman *et al*., 2010). This is unlikely to be feasible in low income regions (Chakraborti *et al*., 2011; Jiménez, 2011). At the present time, despite improvements in some regions, water pollution is on the rise globally, and more than 80% of the municipal wastewater in low income countries is discharged untreated into water bodies or to the ground (UNICEF-WHO, 2012; WWAP, 2009). In addition, the disposal of wastewater or faecal sludge is a concern that is just beginning to be studied (*low to medium confidence, limited evidence*) (Seidu *et al*., 2013).

3.5.2.4. Freshwater Ecosystems

Freshwater ecosystems are comprised by biota (animals, plants and other organisms) and their abiotic environment in slow flowing surface waters like lakes, man-made reservoirs or wetlands, in fast flowing surface waters like rivers and creeks, and in the groundwater. They have suffered more strongly from human actions than marine or terrestrial ecosystems. Between 1970 and 2000, populations of freshwater species included in the Living Planet Index declined on average by 50%, compared to 30% for marine and also for terrestrial species (Millenium Ecosystem Assessment, 2005). Climate change is an additional stressor of freshwater ecosystems. It affects freshwater ecosystems not only by increased water temperatures (discussed in Chapter 4) but also by altered flow regimes, water levels and extent and timing of inundation (Box CC-RF).

Wetlands in semi-arid or arid environments are hotspots of biological diversity and productivity, and are endangered by extinction in case of decreased runoff generation, resulting in wetland extinction and loss of biodiversity (Zacharias and Zamparas, 2010).

In addition, climate change leads to water quality changes (Section 3.2.5) which also influences freshwater ecosystems. Furthermore, freshwater ecosystems are likely to be negatively impacted by human adaptation to climate-change induced flood risk as flood control structures affect the habitat of fish and other biota (Ficke *et al*., 2007).

3.5.2.5. Other Uses

In addition to the direct impacts, vulnerabilities, and risks in the water-related sectors, indirect impacts from changes in the hydrological systems are expected in sectors, such as navigation, transportation, tourism, and urban planning (Badjeck *et al*., 2010; Beniston, 2012; Koetse and Rietveld, 2009; Pinter *et al*., 2006; Rabassa, 2009). Further social and political problems can occur, as for example water scarcity and water overexploitation is *likely* to increase the risks of violent conflicts and nation-state instability (Barnett and Adger, 2007; Buhaug *et al*., 2010; Burke *et al*. 2009; Hsiang *et al*., 2011).

As a consequence of snowline rising and glacier vanishing, damage on environmental, hydrological, geomorphological, heritage, and tourism resources is *very likely* to affect glacierized regions and those communities

active in them (Rabassa, 2009). The melting of alpine glaciers and rising snowlines in the European Alps, South American Andes, or Himalayas already affects for example the tourism industry (Beniston, 2012).

3.5.3. Impact Costs of Extreme Events

Reported flood damages (adjusted to inflation) have increased over the period 1980-2011 from an average of 7 billion US$ per year in the 1980s to about 24 billion US$ per year of which an average of 9% was insured (data from Munich Re, 2012). The SREX report (IPCC, 2012) indicated that economic, including insured, flood disaster losses are higher in developed countries, while fatality rates and economic losses expressed as a proportion of gross domestic product (GDP) are higher in developing countries (Handmer *et al*., 2012). Currently about 800 million people worldwide (i.e. over 11% of global population) are living in flood-prone areas, and about 70 million of those people (i.e. 1% of global population) are, on average, exposed to floods each year (UNISDR, 2011). The population living in flood-prone areas has increased faster than overall population or economic growth (Bouwer *et al*., 2007; Bouwer, 2011; Jongman *et al*., 2012), in part explaining the observed increase in flood damage. Average number of deaths since 1980 is on the order of thousands casualties per year, of which over 95% of deaths occurred in developing countries, with the highest number (75%) are concentrated in southern, south-eastern and eastern Asia (Handmer *et al*., 2012). The loss of life has been decreased considerably, particularly in high income areas, due to improved flood protection and management measures (UNISDR, 2011). One of most vulnerable countries in the Asian region is Pakistan that has been affected by three consecutive years of flooding with nearly 2000 deaths in 2010, followed by 2011 and 2012 which flooding caused at least 360 and 480 deaths respectively.

In the case of events related to extreme precipitation (intense rainfall, hail and flash floods), some studies suggest an increase in impacts related to higher frequency of intense rainfall events (Changnon, 2001; 2009; Jiang *et al*., 2005; Miller *et al*., 2008). The lack of evidence that anthropogenic climate change has led to increasing risks applies mainly to developed countries where detail inventory of weather-related loss data are available over time. Moreover, *robust evidence* that anthropogenic climate change has led to increasing losses cannot be attained as far as changes on peak flows are regionally detected, which may required longer observational records or future risk projections that include exposure and vulnerability changes (Fowler and Wilby, 2010; Bouwer, 2011). In developing countries, high uncertainty in the climate change role on increasing flood risk is mainly related to lack of quality and completeness of loss data, and to the high impacts of modest weather and climate events on the livelihoods and people of informal settlements and economic sectors (Handmer *et al*., 2012). The impacts of local weather extremes are largely excluded in the analysis of impacts as there are not systematically reported or documented on national or global databases. These local weather extremes have increased their direct damage costs to society increasing the statistics on the number of flood disaster, in the sense that even small floods has a potential to cause catastrophic impacts.

Water related impacts (floods and droughts) are projected to increase even in case of constant hazard due to the increase in the population exposed and vulnerability (Kundzewicz, 2013). At global scale, there is a marked regional variability (largest losses in Asia), and a wide range of results between climate models. For instance, analysis from 21 climate models under SRES A1b shows that population exposed by 2050 to a doubling flood frequency range from 31 to 449 million people, and the change in risk varies between -9 and +376% (Arnell and Gosling, 2013a). Detail studies estimating future expected economic losses are mainly focussed in Europe, USA and Australia (Handmer *et al*., 2012; Bouwer *et al*., 2012). In the case of Europe (Feyen *et al*., 2012), the current (control period: 1961-1990) €6.4 billion per year annual damage and 200,000 annual population exposed is expected to increase about twice under scenario B2 (€14-15 billion per year and 440.000-470.000 annual people exposed) and about three times under scenario A2 (€18-21 billion per year and with annual population exposed of 510,000-590,000). According to Handmer *et al*. (2012), the main driver for future increasing losses of water relates disasters in developing countries will be socioeconomic in nature as result of changes in population and exposure of people and assets (based on *medium agreement* and *limited evidence*), with effects of climate change amplifying the impacts of expected losses

The costs of inland waterway transport is *likely* to increase due to increased frequency of low water levels, as e.g. was shown in the impositions of ship draft restrictions during the El Niño 1996. Most direct impacts and costs are

still uncertain and ambiguous (Koetse and Rietveld, 2009). On the other hand, extreme high water levels in rivers is *likely* to increasing sedimentation of navigation channels and hence cause higher costs for navigation due to more necessary channel dredging (Pinter *et al*., 2006).

3.6. Adaptation and Managing Risks

In the face of impacts on water resources, floods and droughts and the changes in water use because of climate change, there is need for adaptation and to increase resilience. Moreover, even to take advantages of possible positive impacts there is need for adaptation. Managing the changing risks due to the impacts of climate change is the key in the adaptation in water sectors (IPCC, 2012), and risk management should be part of decision making and used to deal with uncertainty (ISO 31000, Risk Management (ISO, 2009)). In the next sections, in a generic way, adaptation options are discussed, followed by some reflections on the limits for adaptation and its costs. The need to build capacity in this area is also discussed.

3.6.1. Adaptation Options

Since the 3rd IPCC assessment report efforts have been made to identify options for adaptation in the water sector. Many of them are or were applied simply as a response to climate variability and not directly climate change. Climate change provides many opportunities for improvements as “no regret” actions, which are actions able to generate net social and/or economic benefits can be implemented to address both climate variability and climate change. Table 3-3 present different categories of adaptation options reported in the literature.

[INSERT TABLE 3-3 HERE
Table 3-3: Categories of climate change adaptation measures regarding to freshwater.
CC: Particular relevant to climate change, M+A: assist both mitigation and adaptation, M: also assist mitigation]

Adaptation measures, which involve a combination of ‘hard’ infrastructural and ‘soft’ institutional actions, can be helpful in reducing vulnerability. Individual regional measures can be identified by ‘climate proofing’ and implemented as various actions, such as implementing low-regret flood-risk management programs and conduct capacity building (Bates *et al*., 2008; Cooley, 2008; Mertz *et al*., 2009; Olhoff and Schaer, 2010; Sadoff and Muller, 2009; UNECE, 2009).

To avoid adaptation measures with negative results “maladaptation”, scientific research results can be analyzed preceding the planning. Furthermore, low-regret or no-regret adaptation options, where moderate levels of investment increases the capacity to cope with projected risks or where the investment is justified under all plausible future scenarios, might be aspired (World Bank, 2007). One option to obviate maladaptation is to identify and evaluate the use of virtual water in the countries receiving commodities, and to include externalities in the pricing of exports.

A major instrument to explore water-related adaptation measures to climate change is provided with the Integrated Water Resource Management (IWRM), which can be joined with a Strategic Environmental Assessment (SEA) for introducing environmental considerations into IWRM. IWRM is an internationally accepted approach for efficient, equitable and sustainable development and management of water resources and water demands to ensure productive and healthy ecosystems by integrating social, economic, physical, and biological needs and values (GEF-ADB, 2006). In parallel to the implementation of the IWRM approach there is an increase in the attention to adaptive management and robust measures (European Communities, 2009). A robust measure can be defined as a measure that performs well under different future conditions and clearly optimizes prevailing strategies (Sigel *et al.*, 2010).

Past experience suggests that adaptations are best achieved through mainstreaming and integrating climate responses into sustainable development and poverty eradication processes, rather than by identifying and treating them separately (Elasha, 2008). The rationale for integrating adaptation into development strategies and practices is

underlined by the fact that many of the interventions required to increase resilience to climatic changes generally benefit development objectives.

Water development and planning processes in light of climate change and uncertainty in future hydrological conditions are well discussed (Bates *et al*., 2008). Integrating water resources management on actors, reshaping planning processes, coordinating land and water resource management, recognizing water quality and quality linkages, conjunctive use of surface and ground water and protecting and restoring natural systems have been given priority in water management aspects.

3.6.2 Limits to Adaptation

Limits to Adaptation are discussed in detail in Chapter 16 (Section 16.5). Here, barriers to adaptations referring to freshwater resources are highlighted (Burton, 2008). Barriers such as lack of technical capacity, financial resources, awareness, communication etc., are relevant to freshwater resources management. Some of the barriers that are of importance besides technical aspects are the social and economic ones, such as (Butscher and Huggenberger, 2009; Zwolsman *et al*., 2010; Browning-Aiken and Morehouse, 2006): (a) the fact that poor people settle in unsafe areas lacking water services and therefore demand additional public assistance; (b) migration patterns result in demand for services in new areas, sometimes on a temporary basis, resulting in a loss of local knowledge which would aid the selection of low risk areas for settlement; (c) the need to employ better trained staff to deal with problems of water scarcity, which generally only have complex solutions; (d) the need to enforce the law to better use and protect water sources in places where this is not customary; (e) the management of water demand among users in order to satisfy the need for municipal water, including that required for food and energy production.

3.6.3 Dealing with Uncertainty

One of the key challenges to the incorporation of climate change into water resources management lies in the uncertainty in the projected future changes. A large part of the international literature focuses on this uncertainty, mostly concerned with the development of approaches to quantify uncertainty, and a major component of the approaches to water management in the face of climate change (Section 3.6.6) is their treatment of uncertainty.

Some approaches (e.g. in England and Wales; Arnell, 2011a) use a small set of climate scenarios to characterise the potential range in impacts. Much attention, however, has been directed towards methods which use very large numbers of scenarios to produce 'likelihood distributions' of indicators of impact (e.g., Brekke *et al*., 2008; Christierson *et al*., 2012; Hall *et al*., 2012; Lopez *et al*., 2009) for use in risk assessment. The use of multiple scenarios and the temptation to present impacts in terms of probability distributions, however, begs the question of whether such distributions are meaningful (*cross reference to WG2 scenarios chapter*). It has been argued (Dessai *et al*., 2009; Hall, 2007; Stainforth *et al*., 2007) that the attempt to construct probability distributions of impacts is misguided, largely because of the "deep" uncertainty in possible future climates. Deep uncertainty arises because analysts do not know, or cannot agree upon, how systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth *et al*. (2007) and others therefore argue that it is impossible for practical purposes to construct robust quantitative probability distributions of climate change impacts, and climate change uncertainty needs to be represented differently, for example through the use of a smaller number of plausible scenarios and the less literal interpretation of scenario results.

A section of the literature goes further, arguing that climate models are not sufficiently robust or reliable to provide any basis for adaptation (Anagnostopoulos *et al*., 2010; Blöschl and Montanari, 2010; Koutsoyiannis *et al*., 2008; Lins and Cohn, 2011; Stakhiv, 2011; Wilby, 2010). It is argued that current climate models are frequently biased, and do not reproduce the temporal characteristics -specifically persistence- often found in hydrological records. Existing water resources planning methods, which incorporate uncertainty stochastically and can take persistence into account, are therefore sufficient to address the effects of climate change (Lins and Cohn, 2011; Stakhiv, 2011). This view of climate model performance has been challenged and is the subject of some debate (Huard, 2011;

Koutsoyiannis *et al*., 2011); the critique also assumes that adaptation assessment procedures would only use climate scenarios derived directly from climate model simulations.

Addressing the effects of uncertainty through its quantification in some form of risk assessment, however, is only one way of dealing with uncertainty. An alternative approach starts from the perspective of the characteristics of different adaptation options, and seeks to develop a strategy which is robust and resilient to uncertainty (*cross reference to other WG2 chapters which expand on these terms*) (e.g. Matthews and Wickel, 2009). An example of this approach is provided by Henriques and Spraggs (2011), who considered different responses to future flood risk to critical water supply infrastructure. They used models and scenarios to identify potential risks and their uncertainties, and developed a strategy which enhanced both asset and system resilience. This combined low-regret options to protect individual sites from flooding with longer-term strategies to increase the robustness of the supply network to a wide range of potential disruptions.

Robust decision-making (Lempert *et al*., 1996; 2006; Nassoploulos *et al*., 2012) is a more formalised way of constructing robust and resilient adaptation strategies, and combines features of classic decision analysis and traditional scenario planning. The first stage assesses the performance of a set of defined adaptation actions against a wide range of plausible future conditions. This is similar to traditional scenario planning, but there are two main differences. First, the focus is on adaptation options rather than the future scenarios. Second, the approach involves the assessment of option performance against a very large number of scenarios. The second stage uses the information from the assessment of the initial adaptation options to design revised adaptation options. It does this by identifying, for a given adaptation option, the future scenarios which are particularly challenging, and determining the features of those scenarios that cause problems. The adaptation option is then revised to better cope with these features -and the iteration continues. Even if it is not feasible to identify a single robust strategy (i.e. all the options converge following iteration), the approach does enable the presentation of key tradeoffs and allow decision-makers to determine which risks should be addressed. This approach was applied to the Inland Empire Utilities Agency, supplying water to a region in southern California (Lempert and Groves, 2010). The approach led to the refinement of the company's water resource management plan, making it more robust to the three particularly challenging aspects of climate change identified by the scenario analysis.

3.6.4. Capacity Building

Strengthening the professional capacity and communication on climate change adaptation is essential to cope with the increasing vulnerability to climate change. Capacity building in the water sector means to acquire relevant hydrological and climate information, to make use of this information in water planning processes through e.g. community-based, participatory processes and traditional knowledge, and to acquire financial commitments for adaptation programs. Thus, in implementing successful adaptation measures in the water sector, local people can be properly trained e.g. to manage any instrument or system (e.g., probabilistic decision making tool) that is being set up locally and to transfer technology to low-level water managers. The planning of adaptation projects might be done together with the community so they will understand the use and methodology of appropriate technologies (Bates *et al*., 2008; Halsnæs and Trærup, 2009; Olhoff and Schaer, 2010; Smit and Wandel, 2006; UNECE, 2009; von Storch, 2009).

Finally, the capacity of water management agencies and the water management system as a whole is *likely* to act as a limit on which adaptation measures (if any) can be implemented. The low priority given to water management, lack of coordination between agencies, tensions between national, regional and local scales, ineffective water governance and uncertainty over future climate change impacts constrain the ability of organizations to adapt to changes in water supply and flood risk (Crabbe and Robin, 2006; Ivey *et al*., 2004; Næss *et al*., 2005; Parry *et al*., 2007).

3.6.5. Costs of Adaptation to Climate Change

Considering the importance of adapting to climate change in the water sector, the literature on this topic is relatively limited (EEA, 2007; Kuik *et al*., 2008). Estimates of the costs of adaptation to climate change across sectors at the

global scale were not available until 2006. Since then, five multi-sectoral estimates of these costs have become available (Oxfam, 2007; Stern, 2006; UNDP, 2007; UNFCCC, 2007; World Bank, 2006).

At the local, national, and river basin level, the geographical distribution of these researches is skewed towards developed countries, although examples do exist in developing countries. Adapting urban water infrastructure in sub-Saharan Africa to climate change is estimated to be US$25 billion per year (Muller, 2007). This study assumes that: (a) reliable yields from dams will reduce at the same rate as stream flow (e.g., a 30% reduction in stream flow will mean a 30% reduction in reliable yield, and the unit cost of water will go up by more than 40%); (b) where waste is disposed into streams, a reduction in stream flow by x% will mean that the pollutant load must be reduced by x%; and (c) power generation reduces linearly with stream flow. The costs of adapting existing urban water storage facilities are estimated at $0.05-0.15 billion/year, and the costs of additional new developments are estimated at $0.015-0.05 billion/year. For wastewater treatment, the adaptation costs of existing facilities are estimated at $0.1-0.2 billion/year, and the costs of additional new facilities are estimated at $0.075-0.2 billion/year.

The global costs of adaptation in water resources associated with additional water infrastructure needed.have been assessed (Kirshen, 2007; UNFCCC, 2007; Ward *et al*., 2010). To provide a sufficient water supply, the adaptation costs were estimated to amount to ca. US$531 billion in total for the period up to 2030 given present and future projected water demands and supplies in more than 200 countries (Kirshen, 2007). Of this, US$451 billion (85%) is estimated to be required in developing countries, mainly Asia and Africa. The assessment of Kirshen (2007) was subsequently modified in UNFCCC (2007). In this study, two further costs were included, namely the increased cost of reservoir construction since the best locations have already been taken, and unmet irrigation demands. This report suggests that the total costs of adaptation will be ca. US$898 billion for the period up to 2030. It is assumed that 25% of these costs are specifically related to climate change, and hence the cost of adaptation to climate change in the water supply sector is estimated at ca. US$225 billion up to 2030. This is equivalent to ca. US$11 billion/year (UNFCCC, 2007).

3.6.6. Case Studies

Papers in the refereed literature on adaptation in the water sector fall into four broad groups. One group comprises analyses of the potential effect of different adaptation measures on the impacts of climate change for specific resource systems (for example Connell-Buck *et al*. (2011) and Medellin-Azuara *et al*. (2008) in California, Miles *et al*. (2010) in Washington State USA, Pittock and Finlayson (2011) in the Murray-Darling basin in Australia, and Hoekstra and de Kok (2008) on dike heightening in the Netherlands). The second group presents methodologies for assessing the impacts of climate change specifically for adaptation purposes. For example, Brekke *et al*. (2008; 2009a) and Lopez *et al*. (2009) propose the use of multiple scenarios for risk assessment.

The third group contains approaches for the incorporation of climate change into water resources management practice. A strong theme to this group of studies is the recommendation that water managers should move from the traditional “predict and provide” approach towards adaptive water management (Gersonius *et al*., 2013; Huntjens *et al*., 2012; Mysiak *et al*., 2009; Pahl-Wostl, 2007; Pahl-Wostl *et al*., 2008; Short *et al*., 2012) and the adoption of ‘resilient’ or ‘no-regrets’ approaches (Henriques and Spraggs, 2011; WWAP, 2009). Adaptive water management techniques include scenario planning, employing experimental approaches which involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. These solutions are not entirely technical (or supply-side), and central to the adaptive water management approach is participation and collaboration amongst all stakeholders. However, whilst climate change is frequently cited as a key motivation for the adoption of adaptive water management, there is very little guidance in the literature on precisely how the adaptive water management approach works when addressing climate change over the next few decades. A few examples are given in Ludwig *et al*. (2009). The US Water Utilities Climate Alliance (WUCA, 2010) provide the most comprehensive overview of ways of delivering adaptive water management which explicitly incorporates climate change and its uncertainty. They proposed a framework with three steps -system vulnerability assessment, utility planning using decision -support planning methods, and decision-making and implementation -and summarized planning methods for decision-supports. These include classic decision analysis, traditional scenario planning and robust decision making (Section 3.6.3). Other frameworks that have been proposed based on risk assessment include the threshold-scenario

risk assessment framework (Freas *et al*., 2008), which combines a qualitative threshold risk assessment approach with quantitative scenario-based risk assessment.

The fourth group of studies evaluate the practical and institutional barriers to the incorporation of climate change within water management (Bergsma *et al*., 2012; Engle and Lemos, 2010; Goulden *et al*., 2009; Huntjens *et al*., 2010; Stuart-Hill and Schulze, 2010; Wilby and Vaughan, 2011; Ziervogel *et al*., 2010). The key conclusions from these studies are that institutional structures have the potential to be major barriers to adaptation, that structures which encourage participation and collaboration between stakeholders tend to be most effective, and that the uncertainty in how climate change may affect the water management system is a significant barrier.

There is a considerably smaller literature describing what water management agencies are actually currently doing to adapt to climate change. A number of agencies are beginning to factor climate change into processes and decisions (Kranz *et al*., 2010; Krysanova *et al*., 2010), with the amount of progress strongly influenced by institutional characteristics. This activity largely takes the form of the development of methodologies to be used in practice by water resources and flood managers (e.g. Rudberg *et al*., 2012), and therefore represents attempts to improve adaptive capacity. Much of this activity is reported in the professional 'grey' literature (e.g. Brekke *et al*, 2009a; describing proposed changes to practices in the United States), but some is described in the refereed literature (e.g. Arnell (2011b) describing the evolution of methodologies for water resources assessment under climate change in England and Wales). Several studies report community level activities to reduce exposure to current hydrological variability as a means of adapting to future climate change (e.g. Barrios *et al*., 2009; Gujja *et al*., 2009; Kashaigili *et al*., 2009; Yu *et al*., 2009).

3.7. Linkages with Other Sectors and Services

3.7.1. Impacts of Adaptation in Other Sectors on Freshwater Systems

Adaptation in other sectors such as agriculture and industry might have impacts on the freshwater system and have to be considered while planning adaptation measures in the water sector. For example, improving agricultural land management practices can also lead to reductions in erosion and sedimentation of river channels, while allowing controlled flooding of agricultural land can alleviate flooding in urban areas. Some adaptation measures in other sectors may cause negative impacts in the water sector, e.g. increased irrigation upstream may limit water availability downstream (World Bank, 2007). Furthermore, a project designed for other purposes may also deliver increased climate change resilience as a co-benefit, even without a specifically identified adaptation component (World Bank, 2007; Falloon and Betts, 2010).

3.7.2. Climate Change Mitigation and Freshwater Systems

Many measures for climate change mitigation have an impact on freshwater systems, while freshwater management can affect GHG emissions (Bates *et al*., 2008).

3.7.2.1. Impact of Climate Change Mitigation in Different Sectors on Freshwater Systems

Afforestation of areas suitable according to the Clean Development Mechanism-Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to high and large-scale decreases of long-term average runoff (Trabucco *et al*., 2008). On 80% of the area, runoff is computed to decline by more than 40%, while on 27% runoff decreases by 80-100% were computed, mostly in semi-arid areas (Trabucco *et al*., 2008). For example, economic incentives for carbon sequestration may encourage the expansion of Pinus radiata timber plantations in the Fynbos biome of South Africa, with negative consequences for water supply and biodiversity; afforestation is viable to the forestry industry under current water tariffs and current carbon accounting legislation, but would be unviable if the forestry industry were to pay the true cost of water used by the plantations (Chisholm, 2010). Depending on local conditions, runoff decreases is likely to have beneficial impacts, e.g. on soil erosion,

flood risk, water quality (nitrogen, phosphorus, suspended sediments) and stream habitat quality (Trabucco *et al*., 2008; Wilcock *et al*., 2008).

Renewable energy production in the form of irrigated bioenergy crop production and hydropower generation has negative impacts on freshwater systems (Jacobson, 2009). In the USA, 2% of total consumptive water use in 2005 was due to biofuel production, mainly caused by irrigation of corn for ethanol production, with 2400 m^3 consumptive water use per 1 m^3 of ethanol (King *et al*., 2010). In two scenarios, this fraction increases to 9% in 2030, with future water consumption strongly depending on the degree of irrigation (King *et al*., 2010). Also biofuel crops like switchgrass and jatropha may require irrigation to achieve satisfactory yields. Energy consumption for pumping water for irrigating jatropha in India was estimated to be so high in case of a pumping depth of 60 meter that energy gain by higher crop yields under irrigation is lower than the energy consumption for pumping (Gupta *et al*., 2010). For a biofuel production scenario of the International Energy Agency, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030; in some countries biofuel production is likely to lead to a significant percent increase of water consumption (e.g. Germany, Italy and South Africa), while in others it exacerbates a already high water scarcity (e.g. Spain and China) (Gerbens-Leenes *et al*., 2012). Conversion of native Caatinga forest into rainfed castor beans fields for biofuels in semi-arid Northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010), but there is the risk of soil salinization due to rising groundwater tables. Hydropower generation leads to fragmentation of river channels and to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll, 2009; Poff and Zimmerman, 2010). In particular, hydropower operation often leads to fast sub-daily discharge changes that are detrimental to the downstream river ecosystem (Bruno *et al*., 2009; Zimmerman *et al*., 2010). If, in tropical regions, the ratio of hydropower generation to surface area of the related reservoir is less the 1 MW/km^2, the global warming potential (CO_2-eq. emissions from the reservoir per MWh produced) can be higher than in the case of coal use for energy production (Gunkel, 2009).

CO_2 leakage from saline aquifers used for Carbon Capture and Storage (CCS) to freshwater aquifers is very likely to lead to a pH decline of 1-2 units and increased concentrations of metals, uranium and barium (Little and Jackson, 2010). Pressure buildup caused by gas injection could result in brines or brackish water being pushed into freshwater regions of the aquifer (Nicot, 2008). Displacement of brine into potable water has not been included in a screening methodology for CCS sites in the Netherlands (Ramirez *et al*., 2010). Densification of urban areas to reduce traffic emissions is likely to conflict with provisioning additional open space for inundation in case of floods (Hamin and Gurran, 2009).

3.7.2.2. Impact of Water Management on Climate Change Mitigation

A number of water management decisions affect GHG emissions. Water demand management has a significant impact on energy consumption as energy is required to pump and treat water, to heat it, and to treat wastewater. Water supply and treatment consumes approximately 1.4 % of total electricity consumption in Japan in Japanese Fiscal Year 2008 (MLIT, 2011). Rough estimates for the USA result in a water-related energy consumption that is equivalent to 13% of the total electricity production, with 70% due to water heating and 14% due to wastewater treatment (Griffiths-Sattenspiel and Wilson, 2009). Even though 34% of water withdrawals in the USA are for irrigation, only 5% of the water-related energy consumption occurs in the agricultural sector, mainly for groundwater pumping. For China, where agriculture is responsible for 62% of water withdrawals, groundwater pumping for irrigation accounts for only 0.5% of China's emissions, a small fraction of the 17-20% share of agriculture as a whole (Wang *et al*., 2012).

Emissions from peatland drainage in Southeast Asia contribute 1.3-3.1% of current global CO_2 emissions from the combustion of fossil fuels (Hooijer *et al*., 2010). Peatland rewetting in Southeast Asia is very likely to lead to substantial reductions of net GHG emissions (Couwenberg *et al*., 2010). Climate change mitigation by conservation of wetlands will also benefit water quality (House *et al*., 2010). Irrigation has the potential to lead to increased CO_2 storage in soils due to enhanced biomass production without water stress. Irrigation in semi-arid California did not significantly increase soil organic carbon but strongly increased soil inorganic carbon if irrigation water was rich in

Ca (Wu *et al*., 2008). Water management in rice paddies can reduce emissions. If rice paddies are drained at least once during the growing season, with resulting increased water withdrawals, global CH_4 emissions from rice fields could be decreased by 4.1 Tg/a (15%), and no significant increase in N_2O emissions would occur (Yan *et al*., 2009).

3.8. Research and Data Gaps

Precipitation and river discharge are systematically observed, however, the length and availability of data records are unevenly distributed geographically, and information on other relevant variables, such as soil moisture, snow depth and water equivalent, evapotranspiration, groundwater depth and available groundwater resources, and water quality including sediments, is mostly limited in developing countries. Relevant socio-economic data, such as rates of surface water withdrawal and exploitation of ground water by each sector, arterial drainage, long-range diversion, and information on already-implemented autonomous adaptations for securing stable water supply, are limited even in developed countries. In consequence, assessment capability is limited in general, and especially so in developing countries.

Modeling studies have shown that the adaptation of vegetation to changing climate may have large impacts on the partitioning of precipitation into evapotranspiration and runoff. This feedback should be investigated more thoroughly.

Relatively few results are available on the economic aspects of climate-change impacts and adaptation options related to water resources, which are of great practical importance in regional decision-making that aims for the best mix of mitigation and adaptation. Regional damage curves need to be developed, relating the magnitudes of major causes of water-related disasters (such as intense precipitation, surface soil dryness, and storm surges) to the expected costs.

There is a continuing mismatch between the large (~200-km) scale of climate models and the ~20-km catchment scale at which water is managed and adaptations must be implemented. Increasing the spatial resolution of regional and global climate models, or improving the accuracy of methods for downscaling their outputs, can produce information of more relevance to water management, although robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. Climatic extremes of concern in water management generally recur more frequently than the typical engineering criterion of a 1% probability of annual exceedance. Computing capacity will be required to address these problems with more ensemble simulations at high spatial resolution. Robust attribution to anthropogenic climate change of hydrological changes, particularly changes in the frequency of extreme events, is similarly demanding, and further study is required to develop rigorous attribution tools that require less computation.

Interactions among socio-ecological systems are not yet well considered in assessments of the impact of climate change. Particularly, there are few studies on the impacts of mitigation and adaptation measures taken in other sectors on the water sector, and conversely. A valuable advance would be to couple hydrological models, or even the land-surface components of climate models, to data on water-management activities such as reservoir operations, irrigation and urban withdrawals from surface water or groundwater, based on the synthesis of case studies and research achievements from field surveys.

To allow adaptation to climate change by increased reliance of water supply on groundwater and on the coordinated and combined use of ground water and surface water, the following research and data gaps have to be closed:

- Ground-based data on groundwater dynamics and stored groundwater volumes
- A long-term monitoring program for evaluation of the response of groundwater to climate change
- Better understanding of groundwater recharge and groundwater-surface water interactions
- Assessment of experiences of conjunctive use of groundwater and surface water, including managed aquifer recharge

More studies are needed, notably in developing countries, of the impacts of climate change on water quality, and of vulnerability to and ways of adapting to those impacts.

Frequently Asked Questions

FAQ 3.1: How will the availability of water resources be affected by climate change?

Climate models project both increases and decreases of renewable water resources at the regional scale, although sometimes with large uncertainty. Evapotranspiration is very likely to increase over land. Average annual runoff is generally projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions. Reliable surface water supply is likely to decrease in many regions because of changes in seasonal flow regime due ot decreases in snow and ice storage, groundwater recharge, degradation of water quality, and more variable streamflow due to more variable precipitation.

FAQ 3.2: How will floods and flood damages develop due to climate change?

Projected climate change will change the frequency and magnitude of floods, although the amount and sign of change will vary across the globe. There is considerable uncertainty in the magnitude of regional-scale change due to disagreement between simulations of precipitation. Recent modeling of flood hazards suggests that they will increase over more than half of the globe. More frequent intense rainfall (WG1 SOD 12.4.5.5) would increase the frequency of flooding in small catchments, but the limited extent of intense rainfall events makes the implications more uncertain for larger catchments. The magnitude of spring snowmelt floods is likely to decrease, because less precipitation will fall as snow during winter. The few available studies show strong consistency in projecting increases in flood hazards over central and eastern Siberia, parts of south-east Asia including India, East Africa, Central and West Africa, and northern South America, and decreases in flood hazards in parts of North and East Europe, Anatolia, Central-East Asia, central North America, and southern South America.

Flood hazards will increase flood damages worldwide, enhanced by increasing exposure, particularly on flood-prone valley floors and deltas, of people and assets. Flood disasters may be triggered by weather events that are not statistically extreme but are hazardous because of social conditions that increase exposure and vulnerability. Flood losses in many locations will increase in the absence of additional protection measures, but the increase varies strongly with location, climate model, and the method used to assess exposure and vulnerability.

FAQ 3.3: Are climatic changes more serious than other human impacts on freshwater?

It depends. Impacts of climatic changes on freshwater are different in character from those of other stressors such as land-use change, water withdrawal, artificial drainage of wetlands, dam construction, alteration of river morphology, and water pollution. Climatic changes, such as changes in the amount and intensity of precipitation, are global in scope and affect all compartments of the freshwater system (soil, groundwater, lakes, wetlands and watercourses). The relative seriousness of climate-related stress varies depending on the region, the freshwater compartment and the type of stress. For example no other human stress, apart perhaps from deforestation, could have an impact comparable to that of increased flooding due to more intense rainfall. On the other hand, irrigated agriculture has already led, in some semi-arid regions, to streamflow reductions comparable to or worse than those expected from climatic changes. Finally, the answer depends on the time horizon and on the success of climate-change mitigation. Global population is expected to peak in the mid-21st century, while climatic changes may not peak until much later. The impacts of climate change will therefore become progressively more serious relative to those of other human impacts.

FAQ 3.4: How should water management be adapted in the face of climate change?

Water-resource management under uncertain climate change needs to be approached as a part of natural-resource management, integrated with suitable social measures and development of infrastructure. Restoring and protecting freshwater habitats, and managing natural floodplains, are key elements of such an approach. Adaptive measures that may prove particularly effective include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply-sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water re-use, desalination, and more efficient soil and irrigation-water management. Possible examples of maladaptive measures include large projects, such as dams and irrigation systems, that fail to offer complete flood protection and that harm the adaptive capacity of other sectors; and unreasonably resource-intensive desalination, pumping of deep groundwater, or water treatment.

FAQ 3.5: Does climate change imply only bad news about water resources?

In a warmer climate the balance between precipitation and evaporation will shift. There will be more of both but not necessarily in the same places. Regions with abundant water at present may have yet more, but regions with deficits may suffer more serious shortages. These changes are already well attested globally, but in most regions it will be some decades before they become statistically detectable. Where water stress is alleviated by glacier meltwater there will be a "meltwater dividend" during the 21st century, although the total yield of meltwater will eventually diminish. Many of the adverse impacts of changes in water resources will be felt in the developing world, where investment in more careful management can be expected to be very cost-effective, for example by improving seasonal availability of water, under climate change.

FAQ 3.6: How are portfolio and no-regrets adaptation measures defined?

A portfolio is a set of measures, defined locally, that are considered promising for adaptation to possible future climates and their variability. The measures can be implemented progressively and flexibly, in a coordinated and complementary way, and can be expected to reduce vulnerability and increase resilience. No-regrets measures are those that will yield benefits regardless of how the climate evolves; they are to be preferred. Providing universal access to safe water is an example of a no-regrets option.

Cross-Chapter Boxes

Box CC-RF. Impact of Climate-Change on Freshwater Ecosystems due to Altered River Flow Regimes

[Petra Döll (Germany), Stuart E. Bunn (Australia)]

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff *et al.*, 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e. changes to the frequency, magnitude, duration and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino *et al.*, 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario, 15% of the global land area may suffer, by the 2050s, from a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, like in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased run-off during winter months (Renofalt *et al.*, 2010).

[INSERT FIGURE RF-1 HERE

Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.]

Because biota are often adapted to a certain level of river flow variability, the larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke *et al.*, 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah *et al.*,

2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5-7% of the global land area, mainly in semi-arid areas (Döll and Müller Schmied, 2012; see Chapter 3, Table 3-2).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme *et al.*, 2010). Eco-regions containing over 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme *et al.*, 2010).

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (chapter 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase, when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C and 3.8°, respectively (van Vliet *et al.*, 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet *et al.*, 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

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Box CC-VW. Active Role of Vegetation in Altering Water Flows Under Climate Change

[Richard Betts (UK), Dieter Gerten (Germany), Petra Döll (Germany)]

Terrestrial vegetation dynamics, carbon and water cycles are closely coupled, for example by the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis, and by feedbacks of land cover and land use change on water cycling.Numerous experimental studies have demonstrated that elevated atmospheric CO_2 concentration leads to reduced opening of stomatal apertures, associated with a decrease in leaf-level transpiration (de Boer *et al.*, 2011; Reddy *et al.*, 2011). This physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (iWUE) of plants, as less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) corroborate this finding, suggesting an increase in iWUE of mature trees by 20.5% between the 1970s and 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011). However, the physiological CO_2 effect is accompanied by structural changes to C3 plants (including all tree species), i.e. increased biomass production, spatial encroachment and, thus, higher transpiration, as confirmed by Free Air CO_2 Enrichment (FACE) techniques (Leakey *et al.*, 2009).

There are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.*, (2006) which suggested that physiological CO_2effects (lower transpiration) contributed to a supposed global increase in runoff seen in

reconstructions by (Labat *et al.*, 2004). However, a more recent dataset (Dai *et al.*, 2009) showed different runoff trends in some areas. Detection of ecosystem influences on terrestrial water flows, hence, critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012).

A key influence on the significance of increased iWUE for large-scale transpiration is whether overall leaf area of primary vegetation has remained approximately constant (Gedney *et al.*, 2006) or has increased in some regions due to structural CO_2effects (as assumed in models by Piao *et al.*, 2007; Gerten *et al.*, 2008). While field-based results vary considerably between sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 200 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009), which is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 rise (McMahon *et al.*, 2010). The net impact of CO_2 on global-scale transpiration and runoff therefore remains poorly constrained.

Moreover, model results differ in terms of the importance of CO_2 effects for historical runoff relative to other drivers such as climate, land use change and irrigation water withdrawal. Other than Gedney *et al.*, (2006), Piao *et al.*, (2007) and Gerten *et al.*, (2008) found that CO_2 effects on global runoff were small relative to effects of precipitation, and that land use change (which often acts to decrease evapotranspiration and to increase runoff) was of second-most importance, as also supported by Sterling *et al.*, (2012) data and model analysis. By contrast, using a shorter time period and a smaller selection of river basins, Alkama *et al.*, 2011(2011) suggested that global effects of land use change on runoff have been negligible. Oliveira *et al.*, 2011(2011) furthermore point to the importance of changes in incident solar radiation and the mediating role of vegetation; their global simulations demonstrate, for example, that a higher diffuse radiation fraction during 1960–1990 increased evapotranspiration in the tropics by 3% due to increased photosynthesis from shaded leaves. Since the anthropogenic component of the precipitation and temperature contributions(i.e. of the radiative CO_2 effect) to runoff trends is not yet established, a full attribution of anthropogenic emissions of CO_2 (and other greenhouse gases)is still missing.

Analogously, there is uncertainty about how vegetation responses to future increases in CO_2 will modulate effects of climate change on the terrestrial water balance.21st-century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when CO_2-induced increases in iWUE are included in addition to climate change (Betts *et al.*, 2007; Murray *et al.*, 2012), potentially reducing an increase in water stress due to rising population or climate change (Wiltshire *et al.*, submitted) – although other models project a smaller response (Cao *et al.*, 2009). Direct effects of CO_2 on plants have been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012), depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the climate are accounted for. The model analysis by Alkama *et al.*, (2010) suggests that although the physiological CO_2 effect will be the second-most important factor for 21st-centuryglobal runoff and although both physiological and structural effects will amplify compared to historic conditions, runoff changes will still primarily follow the projected climatic changes. Using a large ensemble of climate change projections, Konzmann *et al.*, (2013) put hydrological changes into an agricultural perspective and suggest that direct CO_2 effects on crops reduce their irrigation requirements (Fig. CC-VW-1). Thus, adverse climate change impacts on crop yields might be partly buffered as iWUE improves (Fader *et al.*, 2010), but only if proper management abates limitation of plant growth by nutrient availability or other factors. Lower transpiration under rising CO_2 may also affect future regional climate change itself (Boucher *et al.*, 2009) and may enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008).

Application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to changes in different climatic variables mediated by vegetation,with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). In a warmer climate with increased atmospheric CO_2 concentration, iWUE of plants increases and leaf area may either increase or decrease, and even though precipitation may slightly decrease, groundwater recharge may increase as a net effect of these interactions (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a location in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier

summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Future anthropogenic and climate-driven land cover and land use changes will also affect regional evapotranspiration, surface and subsurface water flows, with the direction and magnitude of these changes depending on the direction and intensity of the changes in vegetation coverage,as shown e.g. for a river basin in Iowa (Schilling *et al.*, 2008) or for the Elbe river basin (Conradt *et al.*, 2012).Removal of vegetation acting as source of atmospheric moisture can change regional water cycling and decrease potential crop yields by up to 17%in regions otherwise receiving this moisture in the form of precipitation (Bagley *et al.*, 2012).Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the climate system such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011) in that e.g. vegetation structure and composition can dynamically adapt to changing climatic and hydrologic conditions (Gerten *et al.*, 2007), it remains a challenge to disentangle the effects of future land cover changes on the water cycle.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).]

CC-VW References

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Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water

withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use ($kWhr/m^3$) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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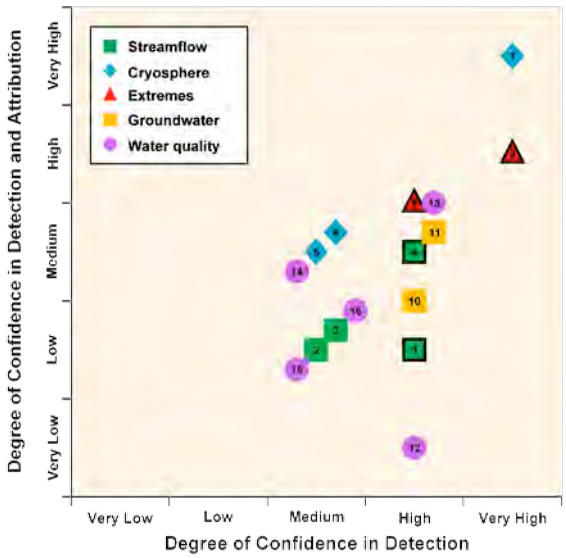
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, which are not all known to be anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.



1: Gedney et al. (2006a), Gerten et al. (2008); 2: Piao et al. (2010); 3: Shiklomanov et al. (2007); 4: Hidalgo et al. (2009); 5: Collins (2008); 6: Baraer et al. (2012); 7: Rosenzweig et al. (2007); 8: Min et al. (2011); 9: Pall et al. (2011); 10: Aguilera and Murillo (2009); 11: Jeelani (2008); 12: Evans et al. (2005); 13: Marcé et al. (2010); 14: Pednekar et al. (2005); 15: Paerl et al. (2006); 16: Tibby and Tiller (2007).

Observed change	*Attributed to*	*Ref*
Changed runoff (global and continental, 1960-1994)	Reduction of transpiration due to anthropogenic CO_2, but partly offset by more abundant vegetation	1
Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	2
Earlier annual peak discharge (Russian Arctic, 1960-2001)	Increased temperature and earlier spring thaw	3
Earlier annual peak discharge (Columbia River, western USA, 1950-1999)	Anthropogenic warming	4
Glacier meltwater yield greater in 1910-1940 than in 1980-2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	5
Decreased dry-season discharge (Peru, 1950s-2000)	Decreased glacier extent in the absence of a clear trend in precipitation	6
Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade	7
More intense extremes of precipitation (northern tropics and mid-latitudes, 1951-1999)	Anthropogenic greenhouse-gas emissions	8
Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	9
Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, increased temperature leading to increased evapotranspiration	10
Decreased groundwater recharge (Kashmir, 1985-2005)	Decreased winter precipitation	11
Increased dissolved organic carbon in upland lakes (United Kingdom, 1988-2004)	Increased temperature and precipitation; multiple confounding factors	12
Increased anoxia in a reservoir, moderated during ENSO episodes (Spain, 1954-2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	13
Variable faecal pollution in a saltwater wetland (California, 1969-2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	14
Nutrient flushing from swamps, reservoirs (North Carolina, 1970s-2002)	Hurricanes	15
Increased lake nutrient content (Victoria, Australia, 1984-2000)	Increased air and water temperature	16

Table 3-2: Hydrological changes and freshwater-related impacts of climate change on humans and ecosystems that could be reduced with lower GHG emissions.

Type of hydrological change or impact	Description of indicator	Hyd. change or impact in different emissions scenarios or different degress of global warming	Reference
Decreace of renewable water resources, global scale	Number of people affected by a water resources decrease of more than 20%, in percent of world population (multi-model mean)	Up to 2°C above present (2.7°C above pre-industrial), each degree of warming affects an additional 7%	Schewe *et al*. (submitted)
Decrease of renewable groundwater resources, global scale	Number of people affected by a groundwater resources decrease of more than 10%, in % of world population by the 2080s (mean and range of 5 GCMs)	RCP2.6: 24% (11-39%) RCP4.5: 26% (23-32%) RCP6.0: 32% (18-45%) RCP8.5: 38% (27-50%)	Portmann *et al.* (submitted)
Change of river discharge in six river basins around the world	Mean annual flows, statistical low flows and high flows	With GW increasing from 1°C to 6°C, the percent changes from historic conditions increase in almost all cases	Gosling *et al*. (2011)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4°C but not for smaller GW	Kingston and Taylor (2010)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Area affected by regime shifts by the 2050s in percent of global land area except Greenland and Antarctica (0.5° grid cell resolution; range of 2 GCMs)	A2: 6.3-7.0 B2: 5.4-6.7	Döll and Müller Schmied (2012)
Change of groundwater recharge in the whole Australian continent	Probability that groundwater recharge decreases to less than 50% of 20th century value by 2050), based on ensemble of 16 GCMs	GW 1.0°C: close to 0 almost everywhere GW 2.4°C: in western Australia 0.2-0.6, in central Australia 0.2-0.3, elsewhere close to 1	Crosbie *et al*. (2012)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	A1f: -26 B1: -22	Holman *et al*. (2009)
Change of river discharge, groundwater recharge and hydraulic head in groundwater in two regions of Denmark		Changes for B2 often larger than for A2	Van Roosmalen *et al*. (2007)
Population living in regions with high water stress	Percentage of global population living in regions of with a per-capita water availability of 1000 m^3/year (2080s, 1 GCM), population according to A2[1]	GW by 2050: 1°C: 62 2°C: 60 4°C: 55	Murray *et al*. (2012)
Salinization of artificial coastal lake IJsselmeer in the Netherlands (a drinking water source)	1 Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg/l)	GW 1°C, no change in atmosph. circulation: 3.1%, 124 days GW 2°C and change in	Bonte and Zwolsman (2010)

	2 Maximum duration of MAC exceedance (2050, 1 GCM)	atmosph. circulation: 14.3 %, 178 days Reference period: 2.5%, 103 days	
Decrease of hydropower production at Lake Nasser, Egypt	Mean decrease of mean annual hydropower production by the 2050s, in % of current hydropower production (11 GCMs)	A2: 7 B1: 8	Beyene *et al*. (2010)
Reduction in usable capacity of once-through or combination cooling thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with with a capacity reduction of more than 50% (for existing power plants) (2031-2060, 3 GCMs)	A2: 24 B1: 22 Without climate change: 16	van Vliet *et al*. (2012)
Flood damages in Europe (EU27)	1 Expected annual damages, in 2006- € 2 Expected annual population exposed (2080s, 2 GCMs)	A2: 18-21 billion €/year , 510.000-590.000 people B2: 14-15 billion €/year , 440.000-470.000 people Reference period: 6.4 billion €/year, 200.000 people	Feyen *et al*. (2012)
Flood damages in Japan	Expected annual damages, in Japanese Yen (¥)	Current 110 billion ¥/year, GCM20 (A1B): 200 billion ¥/year, MIROC-5 (RCP4.5) 150-500 billion ¥/year, MIROC-5 (RCP8.5) 150-330 billion ¥/year.	Fukubayashi *et al*. (2013)

GW: Global warming: mean global temperature increase relative to 1961-90
GCM: General circulation models

Table 3-3: Categories of climate change adaptation measures regarding to freshwater.
CC: Particular relevant to climate change, M+A: assist both mitigation and adaptation, M: also assist mitigation]

ADAPTATION OPTION	CC	M+A	M
Institutional			
Support integrated water resources management (IWRM) , including also the integrated management of land considering specifically negative and positive impacts of climate change		X	X
Promote synergy of water and energy savings and efficient use	X		X
Identify “no-regret policies” and build a portfolio of relevant solutions for adaptation	X		
Increase resilience by forming water utility network working teams	X		
Build adaptive capacity	X		
Improve and share information	X	X	X
Adapt the legal framework to make it instrumental to address climate change impacts	X	X	X
Develop financial tools (credit, subsidies and public investment) for the sustainable management of water, and considering poverty eradication and equity			

Design and operation			
Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	X		
Revise design criteria of water infrastructure to optimize flexibility, redundancy and robustness	X		
Ensure plans and services are robust, adaptable or modular, good value, maintainable, and with long-term benefits, especially in low income countries	X		
Operate water infrastructure increasing the resilience to climate change by all users and sectors			
Take advantage of using hard and soft adaptation measures			X
Perform programs to protect water resources in quantity and quality			
Increase resilience to climate change by diversifying water sources and improving the reservoir management			
Reduce water abstractions by reducing leaks, implementing water saving programs, cascading and reusing water	X	X (leaks)	
Improve design and operation of sewers and wastewater treatment infrastructure to cope with variations in influent quantity and quality	X		
Provide universal sanitation using technology and methodologies locally adapted and provided the proper disposal/reintegration of used water into the environment or its reuse			
Reduce impact of natural disasters			
Implement monitoring and early warning system			
Develop contingency plans			
Improve defense and site selection for key infrastructure that is at risk of floods	X		
Design cities suppressing and resilient to urban floods			
Actively seek and secure water from a diversity (spatially and source-type) of sources within the region to prevent impacts from droughts			
Promote the efficient use of water from all users and reduction of water demand			
Improve irrigation efficiency and reduce the demand of water for irrigation			X
Promote switching to more appropriate crops (drought resistant, saline resistant; low water demand)			
Apply flood or drought resistant crop varieties	X		
Agricultural irrigation			
Reuse wastewater to irrigate crops and use soil for carbon sequestration	X(partly)		X
Industrial use			
When selecting alternative sources of energy, assess the need for water			
Relocate water-thirsty industries and crops to water rich areas			
Implement industrial water efficiency certifications			

With information from: Arkell *et al*. (2011a; 2011b); Andrews (2009); Bahri (2009); Bowes *et al*., (2012); de Graaf and van der Brugge (2010); Dembo (2010); Dillon and Jiménez (2008); Elliot *et al*. (2011); Emelko *et al*. (2011); Godfrey *et al*. (2010) ; Jiménez (2011); Jiménez and Asano (2008b) ; Keller (2008) ; Kingsford (2011); Mackay (2010); Major *et al*. (2011); Marsalek *et al*. (2006); McCafferty (2008); McGuckin (2008); Mukhopadhyay and Dutta (2010); Munashinghe (2010); Mogaka *et al*. (2006); NACWA (2009); OECD (2010); OFWAT (2009); Reiter (2009); Renofalt *et al*. (2010); Seah (2008); Sprenger *et al*. (2011); Thöle (2008); UNESCO (2011); UNHABITAT (2008); Vörösmarty *et al*. (2000); Whitehead *et al*. (2009b); Zwolsman *et al*. (2010)

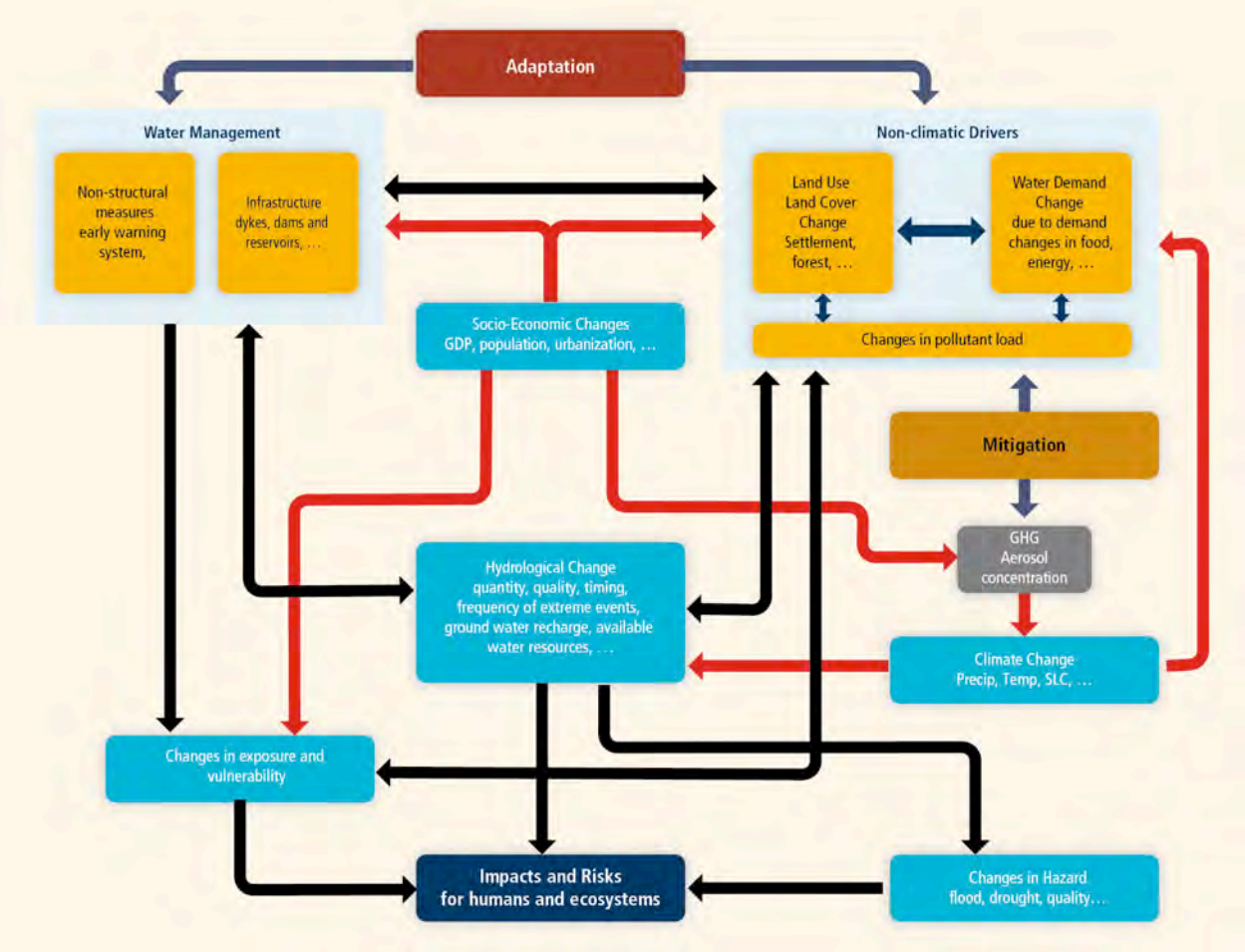


Figure 3-1: Framework for considering the impacts of climate change on freshwater systems and society. Socio-economic changes, such as GDP, population, and urbanization, will change the way of water managements, exposure and vulnerability of human beings against water related risks, and non-climatic drivers changing water management in terms of quantity and quality, as well as emissions and concentration of Green House Gases (GHGs) and Aerosol, that will lead to changes in precipitation, temperature, and sea level. Water management, non-climatic drivers, and climate change will alter hydrological cycles, and lead to change the impacts and risks for humans and ecosystems in conjunction with the changes in exposure and vulnerability, and hazards such as flood and drought. Water management consists with measures developing infrastructure, such as dykes, dams, and reservoirs, and non-structural measures, such as early warning system. Land cover and land use changes including afforestation, deforestation, and settlement, change of water demand due to economic development and demand changes in food and energy, and anthropogenic changes in pollutant load are examples of non-climatic drivers, and they are inter-acting each other. Mitigation acts on the emission and concentration of GHGs as well as on non-climatic drivers, while adaptation acts on non-climatic drivers and water management which alters exposure and vulnerability. (modified from Figure 3-1, AR4)

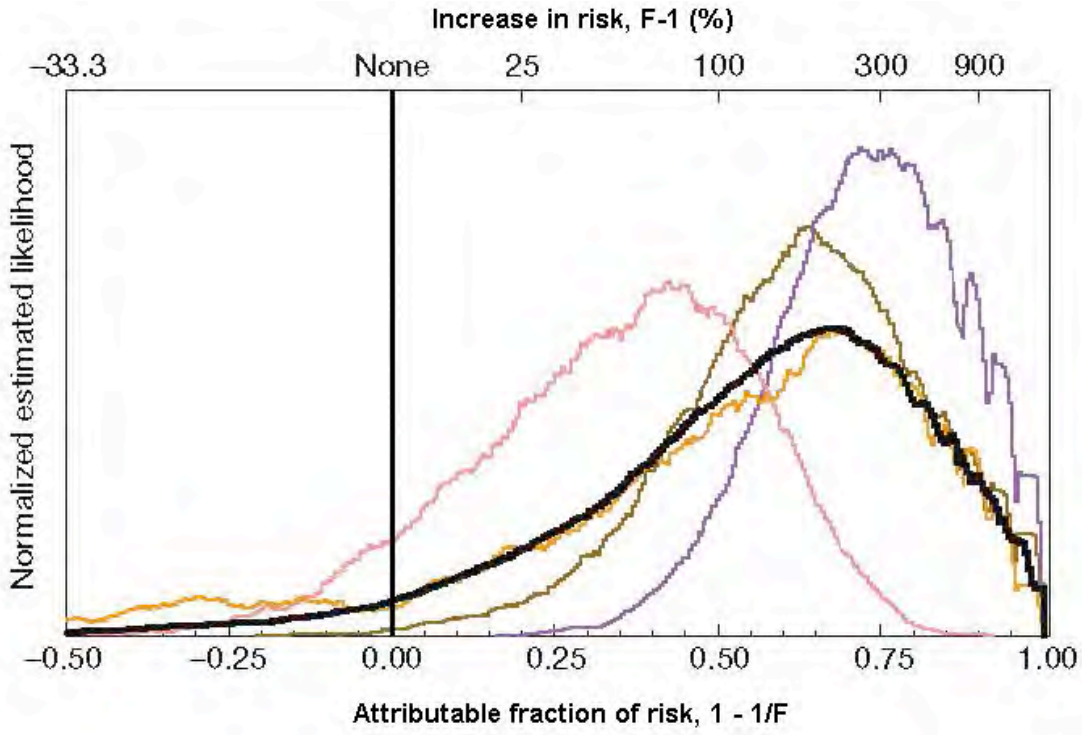
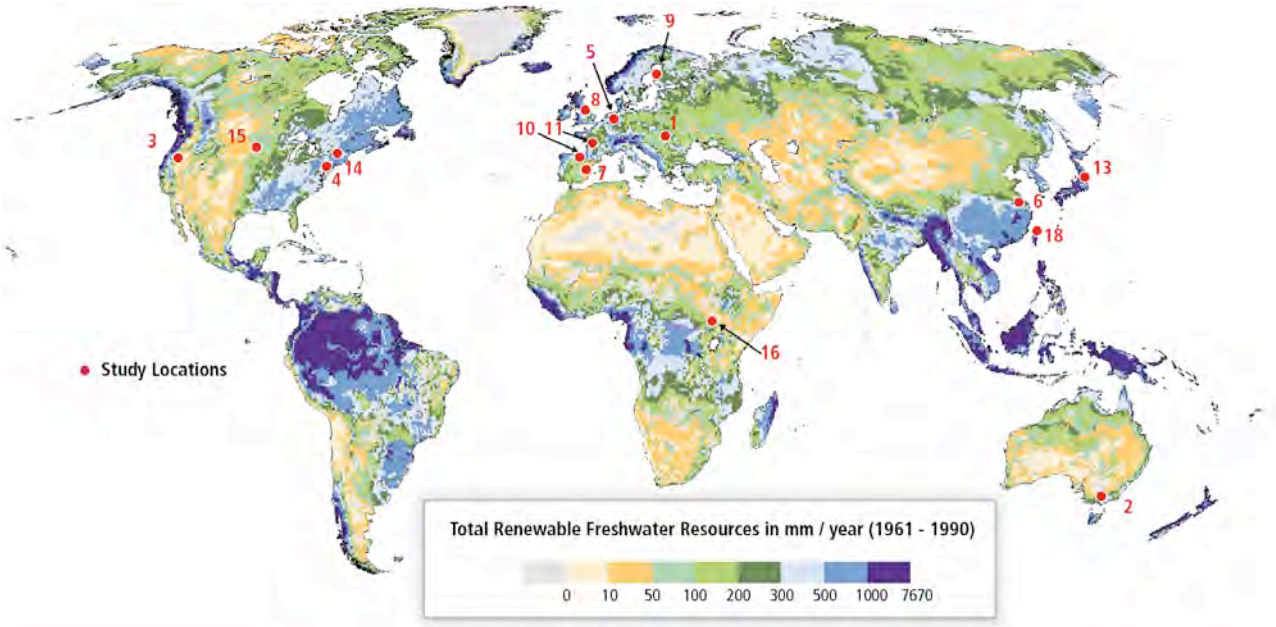


Figure 3-2: Likelihood distributions of the ratio *F* of risks of flooding in England and Wales in autumn 2000 in several thousand paired simulations without and with anthropogenic greenhouse forcing (based on Pall *et al*., 2011; see also Bindoff *et al*., 2013 (WGI Chapter 10)). Each pair starts from a unique initial state that differs slightly from a common reference state. Vertical line represents no change in risk due to anthropogenic greenhouse forcing. Thin coloured lines: distributions with anthropogenic forcing, obtained with a seasonal-forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century; the forecast model is coupled to a model of basin-scale runoff and hydraulics. Thick black line: aggregate of the four distributions.



#	Location	Study Period	Observation	Reference
1	Dabube River, Bratsilava, Slovakia	1926-2005	Although the Water temperature is rising the trend of the weighted long term average temperature valus is near zero. Nevertheless the interannual distribution of the average monthly discharged was modified	Halmova et al., 2008
2	Purrumbete, Colac & Bullen Merri Lakes, Victoria, Australia	1984-2000	The increase in air temperature associated with the increase in salinity and nutrient content in water. Increase in salinity as results of variations in effective precipitation	Tibby and Tiller, 2007
3	Lake Tahoe, California and Nevada Sates, US	1970-2007	Increased temperature induced increased thermal stability lowered the dissolved oxygen content	Sahoo et al., 2010
4	Neuse River Estuary, North Carolina, US	1970-1990s	Large storms and hurricanes assited to flush nutrients from the estuatry reducing eutrophication conditions	Paerl et al., 2006; 2008
5	River Meuse, western Europe	1976-2003	Deterioration of the quality of water in terms or temperature, major elements and some heavy metals and metalloids due to droughts. Higher water temperaturescombined with a reduction of the dilution capacity of point source effluents and longer residence time lead to higher nutrient concentrations that induced algae blooms	Van Vliet and Zwolsman, 2008
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake that was suffering increased frequencies, intensities and more larger of cyanobacterial blooms. In May, 2007, it suffered an unusual massive bloom that lead to the presence of Microcystis toxins in water. This forced two million people from Taihu city to dring bottled water for a week. This was attributed to an unusually warm spring	Qin et al., 2010
7	Sau Reservoir, Spain	1964-2007	Stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen from water	Marce et al., 2010
8	22 upland waters in UK	1988-2002	Dissolved organic increase due to a range of potential drivers, including temperature, rainfall, acid deposition, land-use, nitrogen and CO2 enrichment	Evans et al., 2005
9	Coastal rivers from western Finland	1913-2007	pH (low values) were associated with maximum discharges in rivers because higher rainfalls in bassins with AS (acid sulphate) soils	Sarinen et al., 2010
		1961-2007	CODMs critical values were associated with maximum discharges in rivers because higher rainfalls in bassins with AS (acid sulphate) soils	
10	15 montan pristine rivers from northern Spain	1973-2005	Clear relationship among air temperature increase and the deterioration of water quality (nutrient and COD content in semi arid streams;	Benítez-Gilabert et al., 2010
11	30 coastal rivers and groundwater of Western France	2-6 years	Inter-annual variations on the nutrient content in surface water were realted to changes on air temperature, rainfall and management practices. These variations were not observed on groundwater because of the delay on the response time and the effect of the soil on water.	Gascuel-Odoux et al., 2011
12	Ginock, Scottia	Near 11years	Higher risks of fecal pollution clearly related to rainfall during the wet period	Tetzlaff et al., 2010
13	Japanese streams		Increases on the air temperature were related to increased on the chemical oxygen demand on water, being these higher than those observed from precipitation in arid and semiarid zones	Ozaki et al., 2003
14	SW Penssylvania waters			Chang 2004
15	US	1948-1994	Rainfall and runoff were implicated in site-specific waterborne disease outbreaks	Curriero et al., 2001
16	Northern and Eastern Uganda	1999-2001 2004, 2007	Elevated concentrations of faecal pathogens in groundwater-fed water supplies during the rainy season	Tunwine et al. 2002, 2003; Taylor et al., 2008
17	Walkerton			Auld et al., 2004
18	Taiwan		Epidemic and contamination with enterovirus of a well for supply due to an increased rainfall rate	Jean et al., 2006

Figure3-3: Observations and projections of the impacts on the quality of water. (under production)

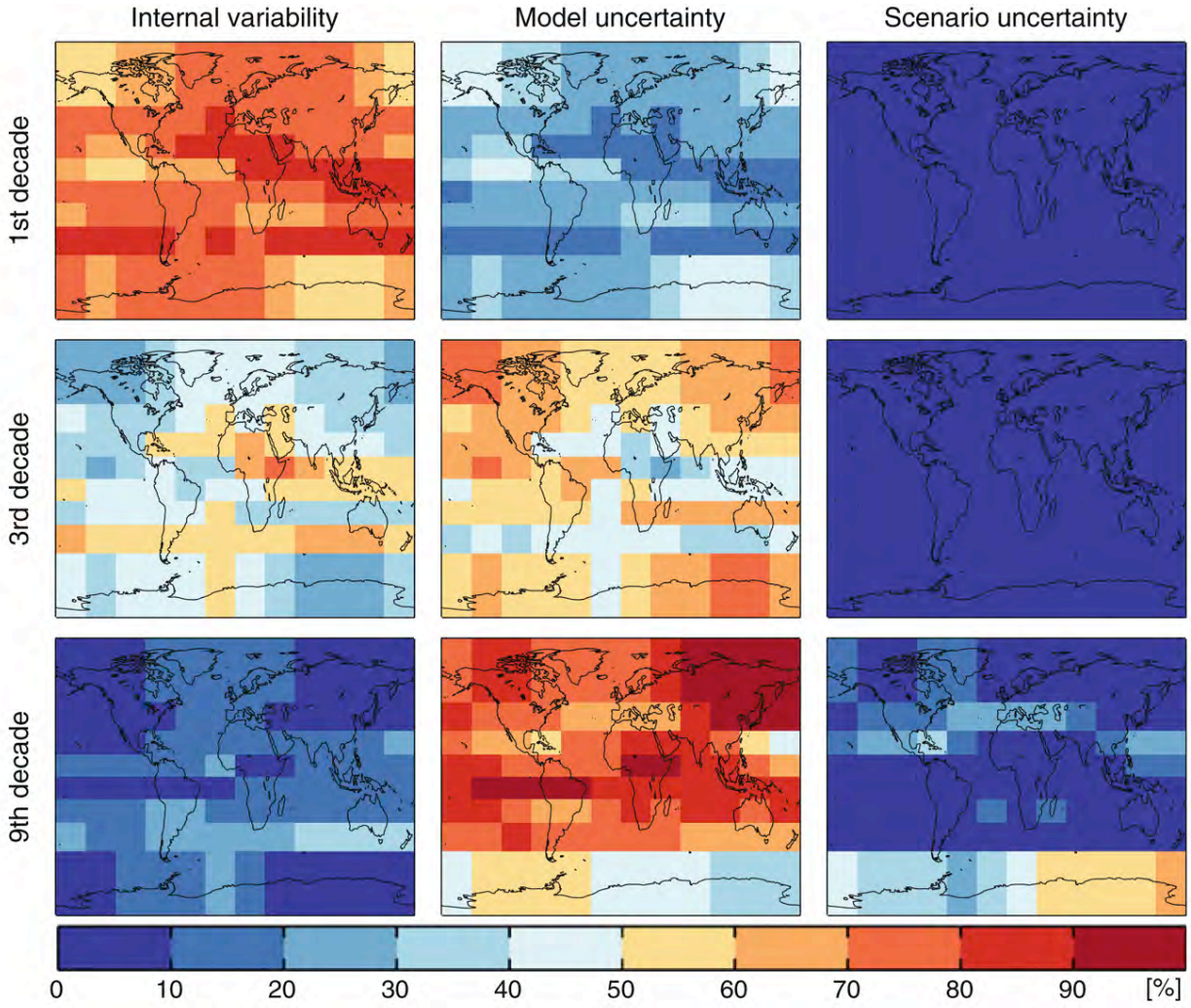


Figure 3-4: Variance in projections of changes in decadal-mean precipitation for boreal summer (June, July, and August), decomposed into contributions from three sources of uncertainty. Simulations were for 2000-2100 under the SRES A1B, A2 and B1 scenarios, with one ensemble member taken from each of 14 CMIP3 GCM experiments. From Hawkins and Sutton (2011).

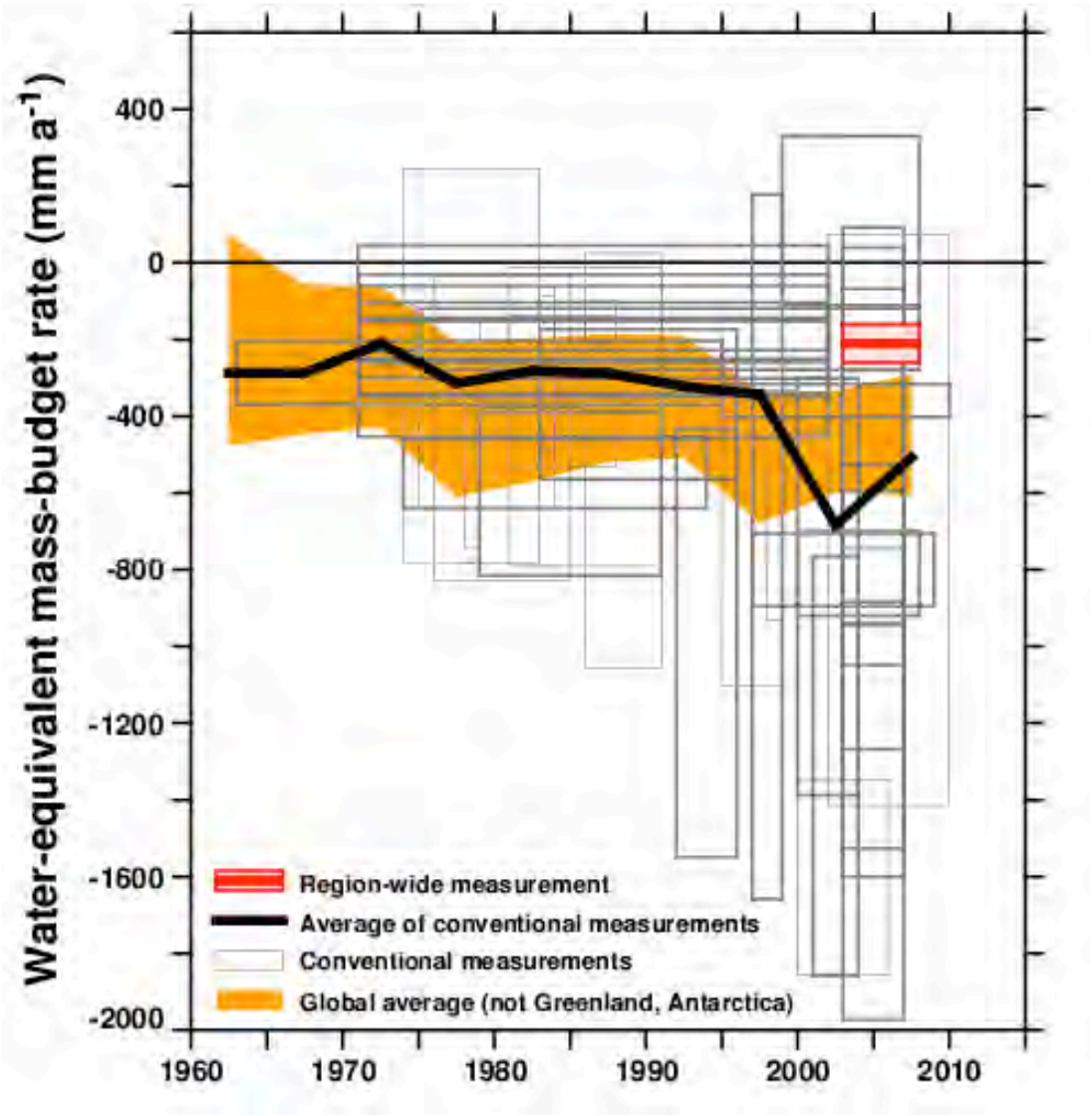


Figure 3-5: A compilation of all published glacier mass balance measurements from the Himalaya (based on Bolch *et al.*, 2012). Each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements). Region-wide measurement (Kääb *et al.*, 2012) was by satellite laser altimetry. Global average (Comiso *et al.*, 2013 (WGI Chapter 4)) is shown as a 1-sigma confidence region.

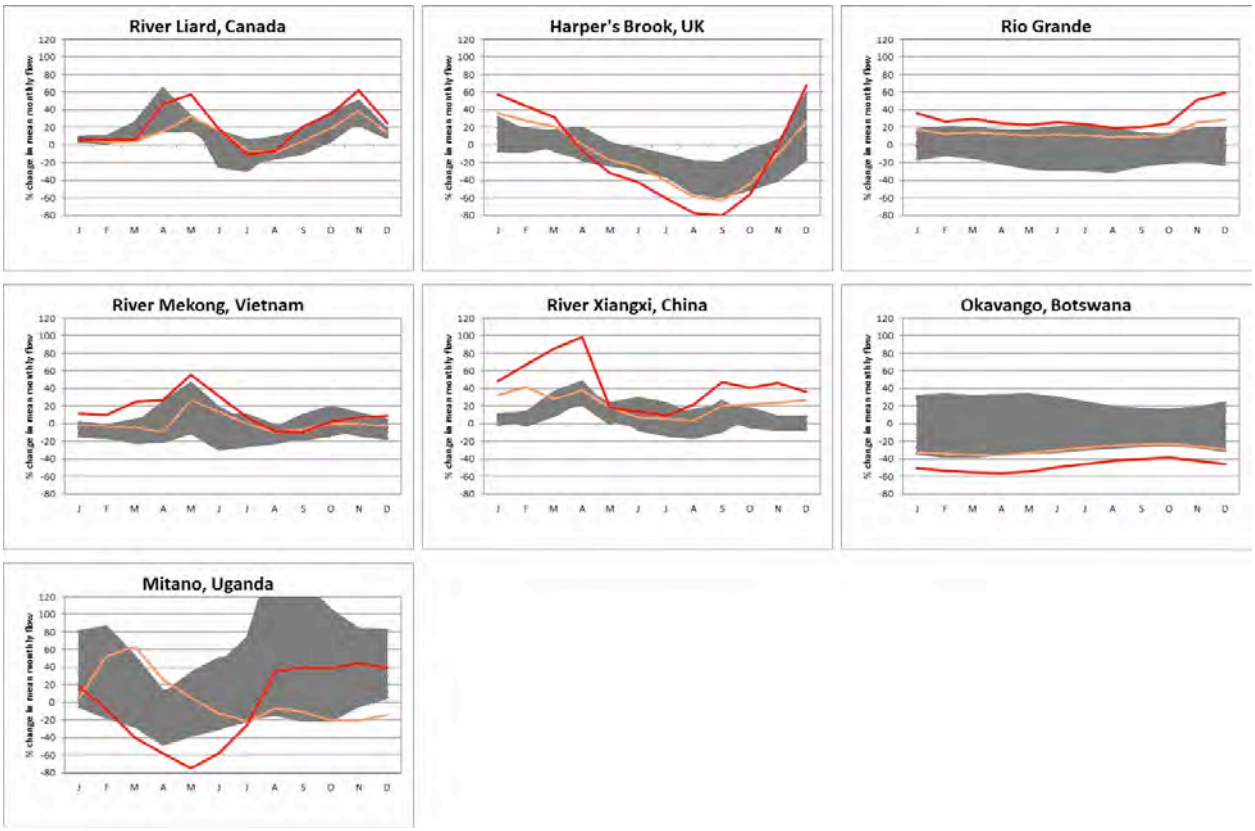


Figure 3-6: Range in change in mean monthly runoff across seven climate models in seven catchments, with a 2°C increase in global mean temperature (above 1961-1990) (Arnell, 2011b; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011a; Xu *et al*., 2011). Changes with the HadCM3 climate model with increases of 2 and 4°C are highlighed.

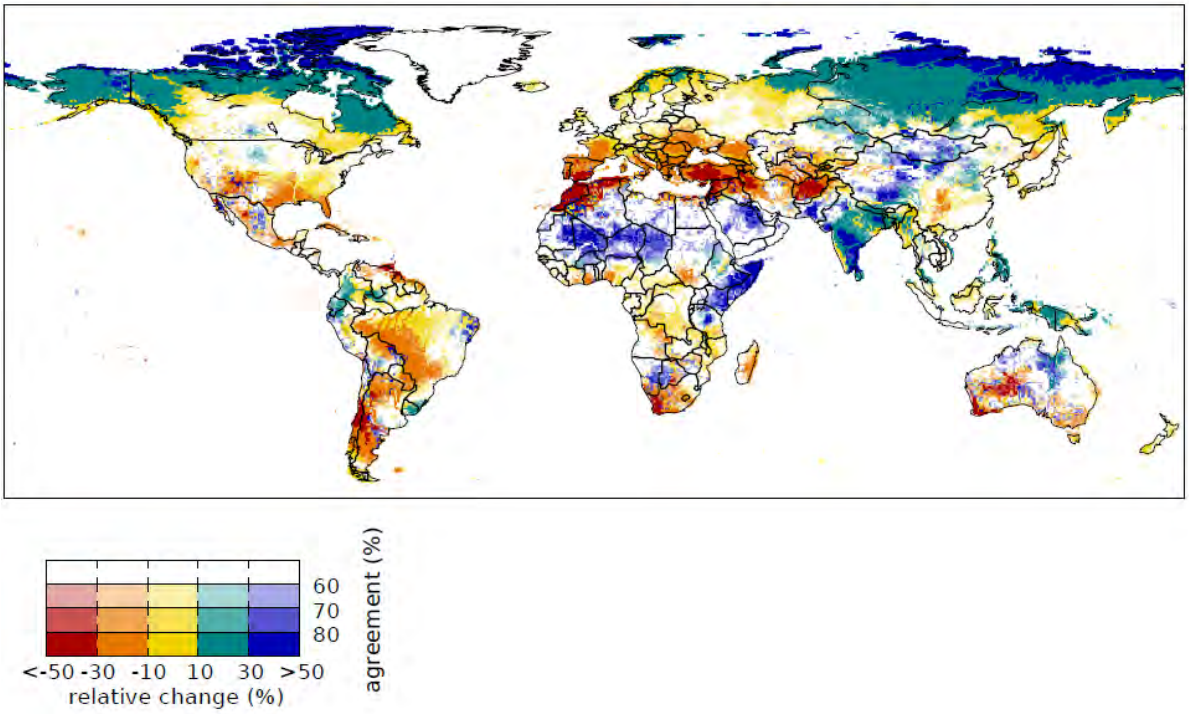


Figure 3-7: Relative change in annual discharge at 2°C (2.7°C above pre-industrial) compared to present-day, under RCP8.5. Color hues show the multi-model mean change, and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign). (Schewe *et al.*, 2013)

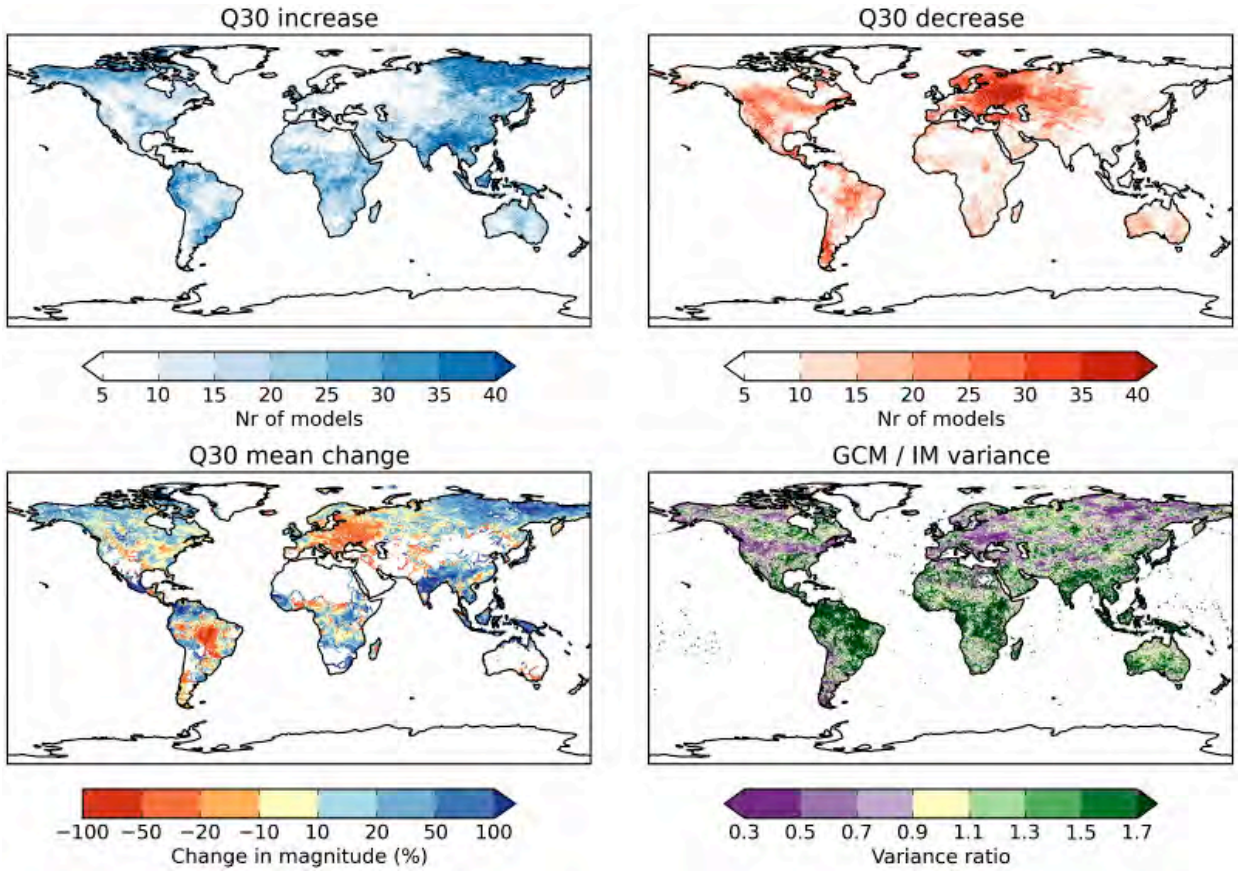


Figure 3-8: Results of flood hazard change for the 30-year return level of river flow (Q30) from ensemble of 5 CMIP5 GCM simulations under RCP8.5 coupled with nine global hydrology and land surface models (named as impact models (IMs)) that provided simulations of daily river discharge at a global 0.5-degree grid for two 30-year periods (1971-2000 and 2070-2090) (Dankers *et al*., 2013). Top: Number of experiments (out of 45 in total) showing an increase (top left) or decrease (top right) in the magnitude of Q30 of more than 10% in 2070-2099 under RCP8.5, compared to 1971-2000. Bottom left: Average change in the magnitude of Q30 across all experiments. Bottom right: Ratio of GCM variance to IM variance. GCM variance was computed as the variance of the change in Q30 across all GCMs for each individual IM, and then averaged over the 9 IMs; IM variance was computed as the variance of the change in Q30 across all IMs for each individual GCM, and then averaged over the 9 GCMs. In dark green (purple) areas GCM (IM) variance predominates.

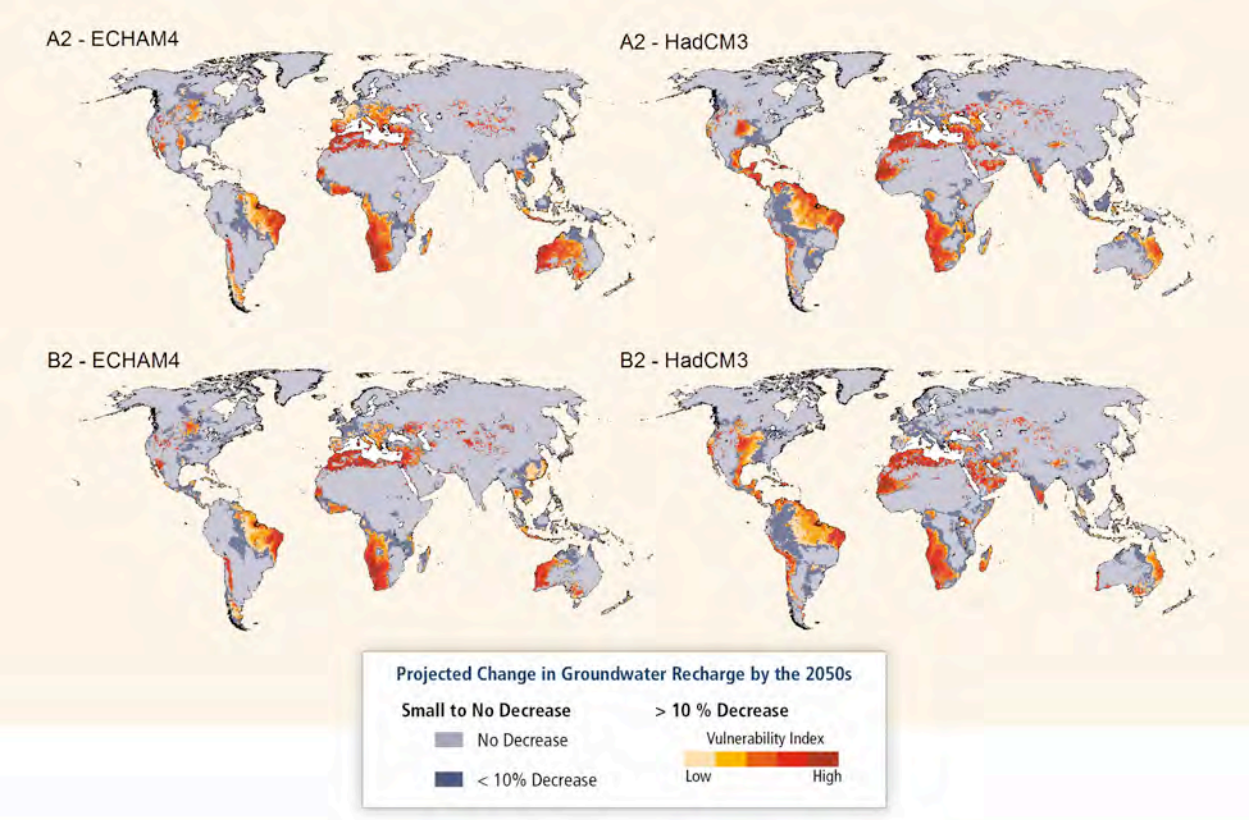


Figure 3-9: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios in which lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percent decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10%, as compared to the climate normal 1961-90 (Döll, 2009).

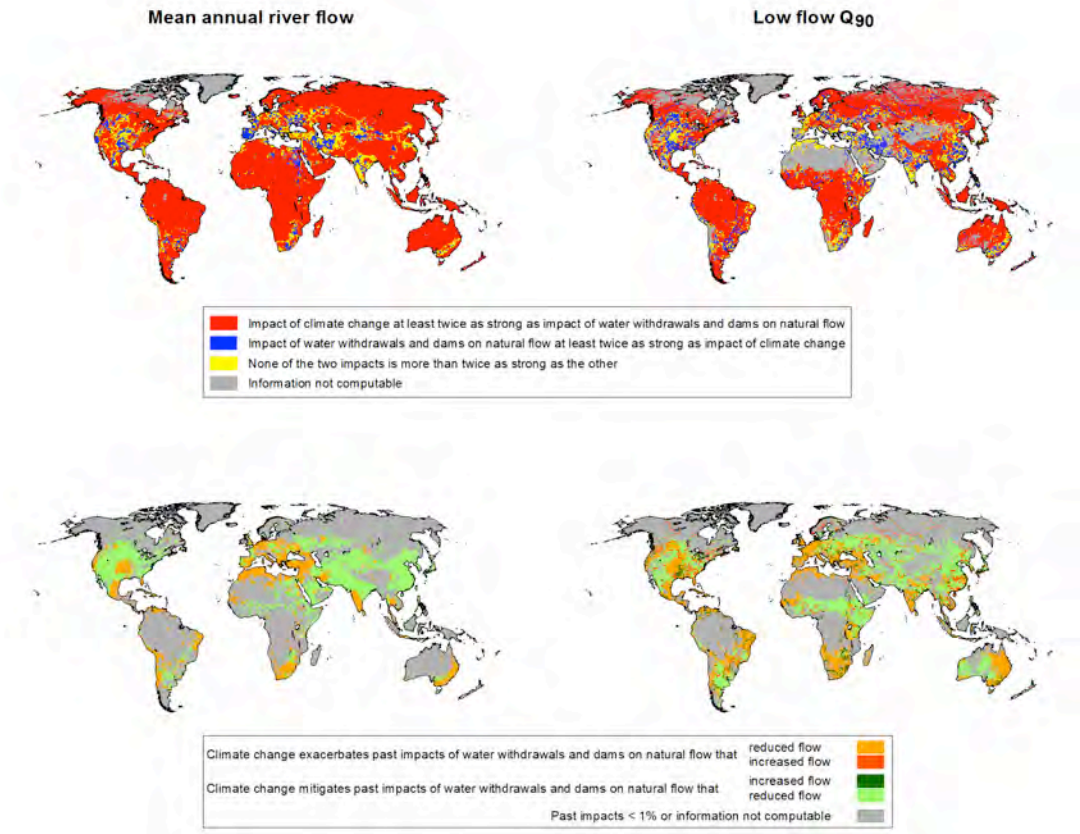


Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.

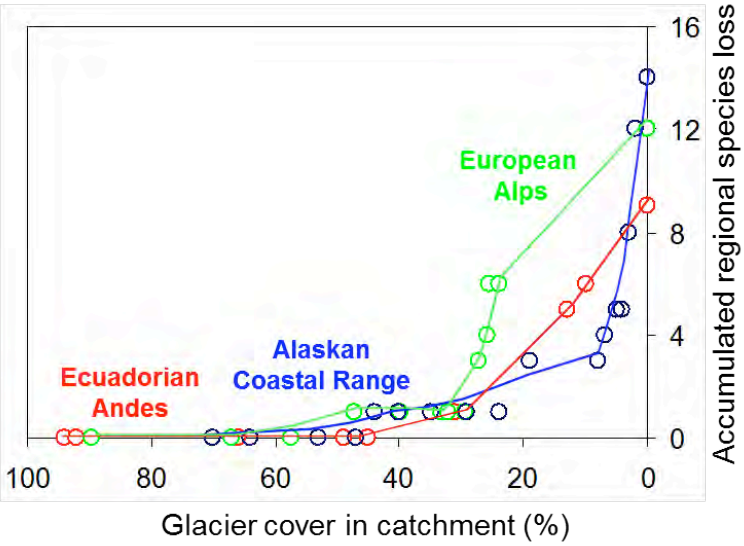


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

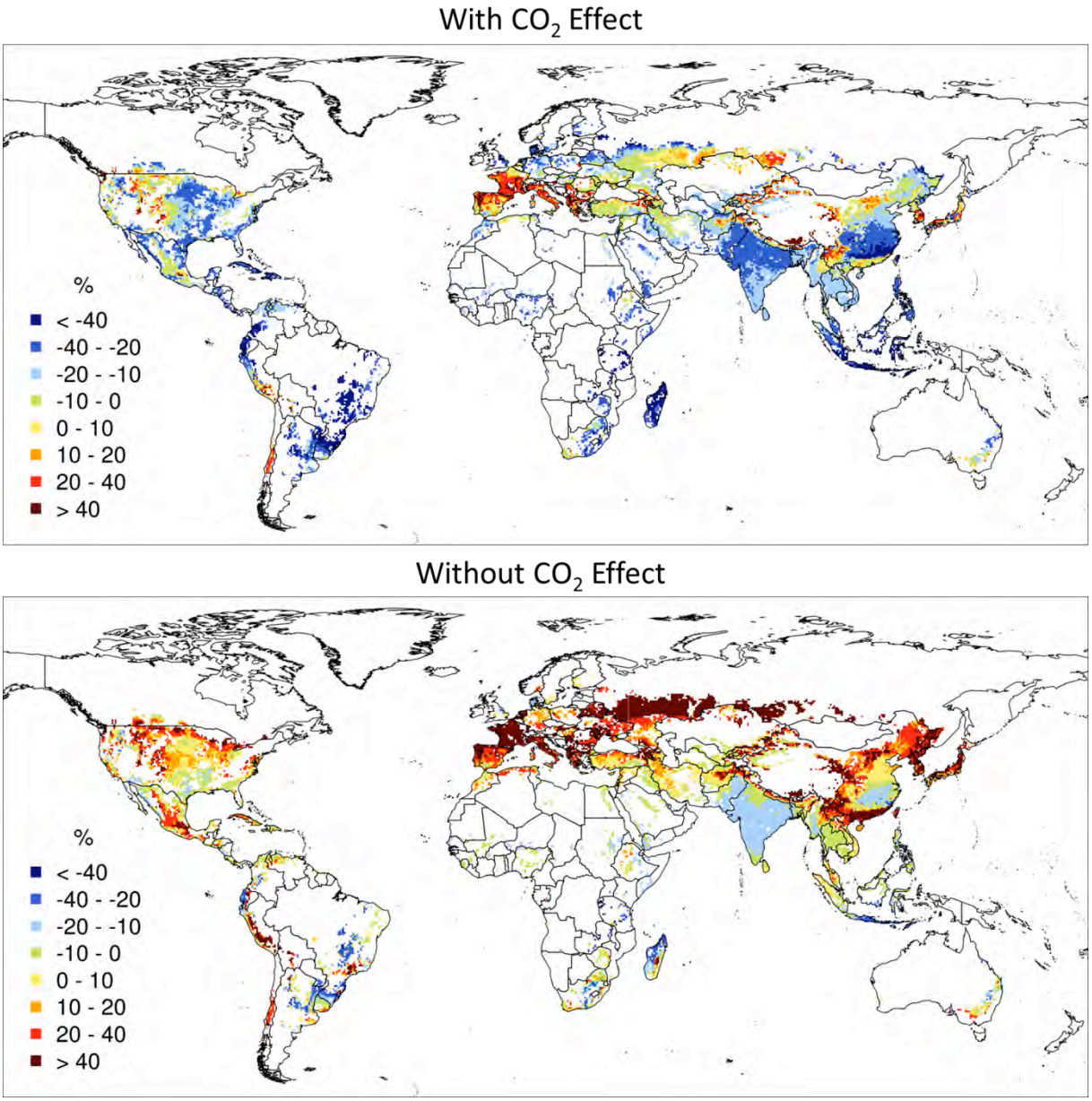


Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).

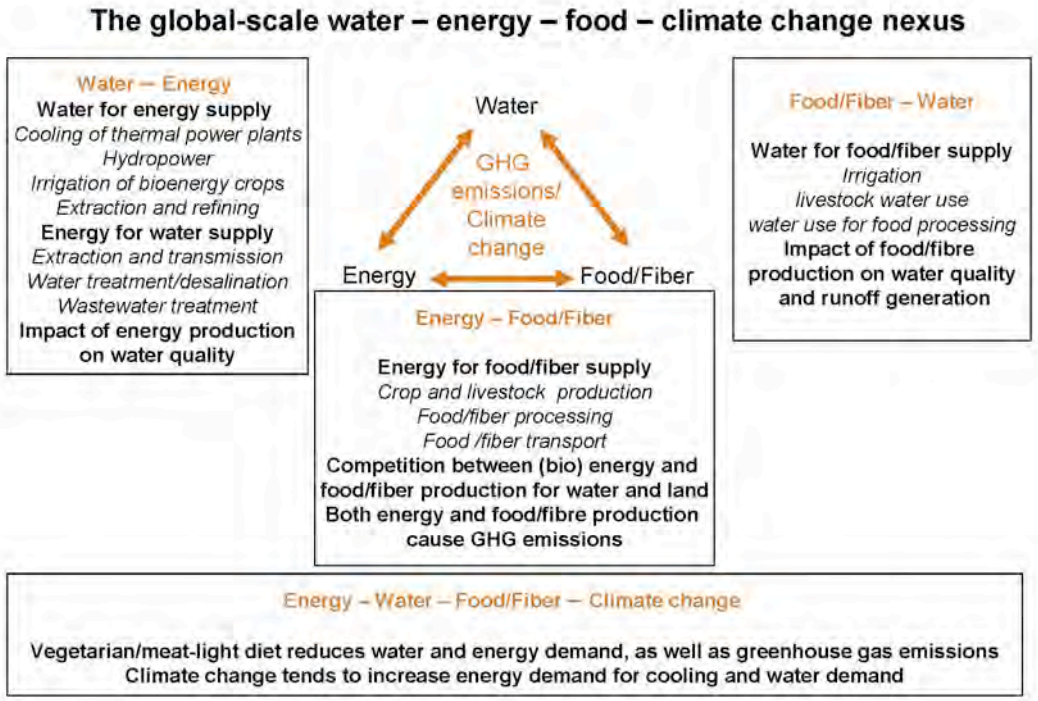


Figure WE-1: The water-energy-food nexus as related to climate change.

Chapter 4. Terrestrial and Inland Water Systems

Coordinating Lead Authors
Robert Scholes (South Africa), Josef Settele (Germany)

Lead Authors
Richard Betts (UK), Stuart Bunn (Australia), Paul Leadley (France), Daniel Nepstad (USA), Jonathan Overpeck (USA), Miguel Angel Taboada (Argentina)

Contributing Authors
Craig Allen (USA), Bill Anderegg (USA), Celine Bellard (France), Paulo Brando (Brazil), Franck Courchamp (France), Wendy Foden (South Africa), Dieter Gerten (Germany), Scott Goetz (USA), Nicola Golding (UK), Patrick Gonzales (USA), Ed Hawkins (UK), Thomas Hickler (Germany), Josh Lawler (USA), Heike Lischke (Switzerland), Georgina Mace (UK), Melodie McGeoch (Australia), Camille Parmesan (USA), Richard Pearson (USA), Beatriz Rodriguez-Labajos (Spain), Rebecca Shaw (USA), Stephen Sitch (UK), Klement Tockner (Germany), Marten Winter (Germany)

Review Editors
Andreas Fischlin (Switzerland), Jose Moreno (Spain), Terry Root (USA)

Volunteer Chapter Scientist
Marten Winter (Germany)

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CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities
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CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

References

Executive Summary

There is *high confidence* that the magnitude of future climate change could approach that of many of the largest climatic changes observed in Earth history. There is also *high confidence* that the planet's biota, carbon cycle and associated feedbacks and services responded to this climate change, even when the rates of past global climate change were slower than implied by higher warming scenarios (e.g., RCP 8.5). [4.2.2] However, the impacts of climate change on terrestrial and freshwater ecosystems must also be considered in the context of non-climatic influences, both naturally-occurring and directly driven by humans. There is *high confidence* that most ecosystems change over time, due to biological interactions and natural environmental disturbances, even under climate change slower than projected for low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). [4.2.2]

Few ecosystems can now be considered to be unaffected by human activity. Vegetation cover classed as "primary" and essentially undisturbed by humans is estimated with *high confidence* to have decreased from approximately 95% of the global land area in 1500 AD to less than 40% at the start of the 21st Century, with half of this reduction being at the expense of primary forest. [4.2.1, 4.2.3, 4.2.4] **There is *medium confidence* that significant feedbacks exist between terrestrial ecosystems and the climate. Thus local, regional and global climate may be affected as ecosystems are altered, through climate change itself or other mechanisms, such as conversion to agriculture or human settlement.** These climate feedbacks are driven by changes in surface albedo, evapotranspiration and greenhouse gas emissions. The regions where the climate is affected may be different from the location of the ecosystem change. [e.g. 4.3.3.4]

There is *high confidence* for freshwater ecosystems and *medium confidence* for terrestrial ecosystems that direct human impacts such as land-use change, pollution and water resource development will continue to dominate the threats to ecosystems, with climate change becoming an increasing additional stress through the century, especially for high-warming scenarios such as RCP6.0 and RCP8.5. [4.3.3] Model-based projections imply that direct land cover change will continue to dominate over climate-induced change for low to moderate warming scenarios at global scales (e.g., RCP2.6 to RCP6.0). However, in many areas not subject to intensive human disturbance, there is *high confidence* that even lower levels of projected future climate changes will result in changes in large-scale ecosystem character depending on the nature of regional climate changes. Such changes may not be fully apparent for several decades after reaching the critical regional climate state, due to long response times in ecological systems (*medium confidence*). For higher warming scenarios, some model projections imply climate-driven large-scale ecosystem changes which become comparable with direct human impacts at the global scale (*medium confidence*). There is *high confidence* that rising water temperatures will lead to shifts in freshwater species distributions and compound water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients. There is *medium confidence* that changes in precipitation will significant alter ecologically important attributes of flow regimes in rivers and wetlands and exacerbate impacts from human water use in developed river basins. [Box CC-RF, 4.3.3.3]

There is *high confidence* that the capacity of many species to respond to climate change will continue to be constrained by non-climate factors, including but not limited to the simultaneous presence of land-use changes, habitat fragmentation and loss, competition with alien species, exposure to novel pests and diseases, nitrogen loading, increasing carbon dioxide and tropospheric ozone. [Figure 4-1, 4.2.4-4.2.4.6, 4.3.3-4.3.3.5]

There is *high confidence* that a changing climate exacerbates other threats to biodiversity. In some systems, such as high altitude and latitude freshwater and terrestrial ecosystems, there is *high confidence* that climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function. [4.3.2.5, 4.3.3.1, 4.3.3.3, 4.4.1.1] Since the specific changes in individual regions depends on the nature of the projected regional climate change, the confidence in specific future ecosystem changes is limited by the confidence assigned to regional climate change projections by Working Group I.

There is *high confidence* that plants and animal species have moved their ranges, altered their abundance and shifted their seasonal activities in response to climate change in the past. There is also *high confidence* that they are doing so now in many regions and will continue to do so in response to projected future climate change. [4.2.2, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3] The broad patterns of species and biome movement towards the poles and higher in altitude in response to a warming climate are well established for the distant (*very high confidence*) and recent past (*medium confidence*). *High confidence* in these past responses, coupled with projections from a diversity of models and studies provide *high confidence* that such responses will be the norm with continued warming. [4.2.1, 4.2.2, 4.3.2, 4.3.2.1, 4.3.2.5] There is *high confidence* that these shifts in species ranges will cause large changes in local abundance under all climate change scenarios: abundance declining in areas where climate becomes unfavorable and potentially increasing in areas where climate becomes more favorable. [4.3.2.5] There is *high confidence* that such changes in species abundance lead to changes in community composition and ecosystem function. There is *high confidence*, based on extensive ground and satellite-based measurements that the seasonal activity of species has responded to warming over the last several decades. [4.3.2, 4.3.2.1, 4.4.1.1] Observations and models of the seasonal activities of species indicate that climate warming disrupts species life cycles and

interactions between species, as well as altering ecosystem function. [4.3.2.1, 4.4.1.1] At local scales, observed and modelled species responses sometimes differ from qualitative predictions based on global scale indices of warming; this can often be explained by large variation in local scale climate response to global warming, changes in climate factors other than average temperature, non-climatic determinants of species distributions, interactions between climate and other simultaneous global change factors such as nitrogen deposition, and species interactions. [4.3.2.1, 4.3.2.5, 4.4.1.1] There is *high confidence* that no past climate changes is a precise analog to the current and projected climatic changes, so species responses inferred from the past only give indications, especially at the local scale. [4.2.2]

There is *high confidence* that climate change is increasing the likelihood of the establishment, growth, spread and survival of some invasive alien species populations in some regions. Alien invasive species are more likely than native species to have traits that favor their survival and reproduction under changing climates. Species movement into areas where they were not present historically will be driven both by climate change and by increased dispersal opportunities associated with human activities. [4.2.4.6]

There is *medium confidence* that even for mid-range rates of climate change (i.e., RCP4.5 and RCP6.0 scenarios) many species will be unable to move fast enough to track suitable climates. Over the last several decades many species have tracked changes in climate. However, there is *medium confidence* that some species have been unable to track recent climatic changes. [4.3.2.5] Populations of species that cannot track future climate change by migrating will find themselves in unfavorable climates and are unable to expand into newly climatically suitable areas. Species in large flat areas are particularly vulnerable because they must migrate over longer distances to keep up with climate change than species in mountainous regions. Species with low migration capacity will also be especially vulnerable: examples include most trees, many plants, and some small mammals. Combinations of low migration capacity and large flat areas are projected to pose the most serious problems for tracking climate; for example, there is *medium confidence* that even the maximum observed and modelled migration rates for mid- and late-successional tree species will be insufficient to track climate change in flat areas even at moderate rates of climate change. There is *high confidence* that barriers to migration such as mountain ranges, dams, habitat fragmentation and occupation of habitat by competing species substantially reduce the ability of species to migrate to more suitable climates. There is *high confidence* that outlier populations (e.g., collections in botanical gardens or parks), as well as intentional and accidental anthropogenic transport will speed migration. [4.3.2.5, 4.3.3.3]

There is *high confidence* that large magnitudes of climate change will negatively impact species with populations that are primarily restricted to protected areas, mountaintops or mountain streams, even those that potentially migrate fast enough to track suitable climates. [4.3.2.5, 4.3.4.1] Climate change is projected with *high confidence* to either create unsuitable climates for species that remain in these areas, or force species out of protected areas and off mountaintops. These effects are foreseen to be modest for low magnitudes of climate change (e.g., RCP 2.6) and very high for the highest magnitudes of projected climate change (e.g., RCP 8.5). There is *high confidence* that species have already started to migrate out of protected areas and towards mountaintops over the last several decades due to a warming climate. [4.3.2.5, 4.3.4.1]

There is *very high confidence* that projected climate changes imply increased extinction risk for a substantial fraction of species during and beyond the 21st century, especially as climate change interacts with other pressures. [4.3.2.5] Uncertainties in regional climate projections, highly variable estimates from comparisons of paleontological extinctions in response to past climate changes, different methods of estimating present and future extinction risk, and the variable adaptive capacity of wild species all contribute to an extremely broad range of estimates of future extinction risk due to climate change. There is *high confidence* that current extinction pressures from habitat modification, over-exploitation and invasive species are continuing, and will interact with growing impacts of climate change. When combined with methodological challenges in modelling future extinction risks, this means there is *low confidence* that global extinction risks due to climate change can be accurately quantified. There is, however, a strong consensus that current climate change pressures and their interactions with other global changes will increase extinction risk for many terrestrial and freshwater species. There is *very low confidence* that observed species extinctions can be attributed to recent climate warming given the very low fraction of species for which global extinction has been ascribed to climate change and tenuous nature of most attributions. However, in

the specific case of Central American amphibians, there is *medium confidence* that recent warming has played a role in their extinctions. [4.3.2, 4.3.2.5]

It is *virtually certain* that the carbon stored in land and freshwater ecosystems in the form of plant biomass and soil organic matter has increased over the past two decades in what is known as the terrestrial carbon sink. There is *low confidence* that the transfer of carbon dioxide from the atmosphere to the land will continue at a similar rate for the remainder of the century. There is *high confidence* that the terrestrial carbon sink is offset to a large degree by carbon released to the atmosphere through forest conversion to farm and grazing land and through forest degradation [4.2.4.1, 4.3.3.1]. There is *medium confidence* that the carbon stored thus far in terrestrial ecosystems is vulnerable to loss back to the atmosphere as a result of climate change (including indirect effects such as increased risk of fires and pest outbreaks) and land-use change. Terrestrial and freshwater ecosystems have been responsible for the uptake of about a quarter of all anthropogenic CO_2 emissions in the past half century. [4.3.2.2 and 4.3.2.3] The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability. As a result there is *low confidence* in the ability to determine whether the net fluxes into or out of terrestrial ecosystems at the global scale have increased or decreased over the past two decades. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. [4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2] Experiments and modelling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate. [4.2.4.4]. There is also *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations and in some places drought, decrease plant productivity by comparable amounts [4.2.4.3, Box 4-3]. Models provide *high confidence* that nitrogen availability will limit the response of many natural ecosystems to rising CO_2. [4.2.4.2]. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors [4.3.2.2, 4.2.2.3].

There is *medium confidence* that increases in the frequency or intensity of ecosystem disturbances due to fires, pest outbreaks, wind-storms and droughts have been detected in many parts of the world. There is *high confidence* that such changes, which are by definition beyond the range of historical natural variability, will alter the structure, composition and functioning of ecosystems. There is *medium confidence* that such changes will often be manifested as relatively abrupt and spatially-patchy transitions following disturbances, rather than gradual and spatially-uniform shifts in location or abundance. [Box 4-3, Box 4-4, 4.2.4.6, 4.3.3, 4.3.2.5, Figure 4-12]

There is evidence of an increase in tree mortality in many regions over the last decade, but there is *low confidence* in the detection of a global trend in increased mortality or in the attribution of such a global trend to climate change. In some regions, increased tree mortality is sufficiently intense and widespread as to result in forest dieback. Forest dieback constitutes a major risk because of its large impacts on biodiversity, wood production, water quality, amenity, economic activity and the climate itself [4.3.2, 4.3.3.1, 4.3.3.4, 4.3.4, Box 4-2, Box 4-3]. In detailed regional studies, particularly in western and boreal North America, there is *high confidence* that observed tree mortality is detectable and can be attributed to the direct effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming.

Recent experimental, observational and modelling studies provide *medium confidence* that forests may be more sensitive to future climate change than reported in IPCC AR4 assessment and that tree mortality and forest dieback could become a problem in many regions much sooner than previously anticipated. [4.3.3.1] There is *high confidence* that future climate change impacts on tree mortality and tree ranges could be large, but experimental, observational and modelling studies also indicate that there is *low confidence* associated with model-based projections of the details of these impacts. As such, projections of increased tree growth and enhanced forest C sequestration mediated by increasing growing season length, rising CO_2 concentrations and atmospheric N deposition are being viewed with increasingly greater caution due to the counter-balancing effects of mortality and dieback. [4.3.3.1] The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products depending on the balance of the positive vs. negative effects of global change. [4.3.3.1, 4.3.3.5, 4.3.4]

In the Amazon, there is *medium confidence* that climate change alone will not lead to widespread forest loss during this century. However, there is also *medium confidence* that a combination of severe drought, land use and fire act together to transform mature forests to less dense, fire prone woodland and shrublands. Modelling studies project a range of changes in the regional climate of the Amazon, and very few indicate a state that cannot support rainforest. Nevertheless, many models still project a general drying tendency, and coupled with warming this may increase fire risk. Human land use is associated with fire, so a combination of direct human influence and climate change may still affect the Amazon. [4.3.3.1.3, Box 4-3]

There is *high confidence* that terrestrial and freshwater ecosystems can, when pushed by climate change, cross "tipping points" and abruptly change in composition, structure and function. There is *medium confidence* that the crossing of these tipping points will result in significant increases in carbon emissions to the atmosphere. This has happened many times in Earth history. [4.2.2]. There are plausible mechanisms, supported by experimental evidence and model results, for the existence of ecosystem tipping points in both boreal-arctic systems and the rainforests of the Amazon basin [Boxes 4-3 and 4-4], others may exist. There is a plausible but *low confidence* case that continued climate change could push the boreal-arctic system across such a tipping point in this century and cause an abrupt transformation of the ecology and albedo of this region, as well as the release of greenhouse gases from the thawing permafrost and burning forests. There is *high confidence* that adaption measures will be unable to prevent substantial change in the boreal-arctic system. There is also a plausible but *low confidence* case that continued climate change together with land-use change and fire activity could cause much of the Amazon forest to transform abruptly to more open, dry-adapted ecosystems, and in doing so, put a large stock of biodiversity at elevated risk, and create a large new net greenhouse gas source to the atmosphere. [4.3.3.1]. There is *medium confidence* that the combination of climate change and land-use change in the Amazon will cause accelerated drying and drought frequency in the region and *low confidence* that these Amazon changes will affect rainfall in agricultural regions elsewhere on the planet. [4.3.3.1]. There is *medium confidence* that rigorously applied adaptation measures could lower the risk of abrupt change in the Amazon, as well as the impacts of that change. [Box 4-3, 4.3.3-4.3.3.4, Figure 4-10]. There is *very high confidence* that policy and market-driven interventions have caused a steep decline in deforestation in the Amazon since 2005 that have decreased anthropogenic carbon emissions to the atmosphere by 1.5%. [4.2.4.1, 4.3.3.1]

There is *high confidence* that management actions can reduce, but not eliminate, exposure to climate-driven ecosystem impacts, as well as increase ecosystem adaptability. [4.4] The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species there is *medium confidence* that this is insufficient to cope without substantial loss of species and ecosystem services, given the rate and magnitude of climate change projected under medium-range warming (e.g., RCP6.0) or high–range warming scenarios (e.g., RCP8.5). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. [4.4.1-4.4.1.2, 4.4.3]

There is *medium confidence* that management adaptation responses to climate change in some sectors will lead to unintended and unwanted outcomes for terrestrial and freshwater ecosystems. For example, adaptation responses to counter increased variability of water supply for urban and agricultural use, such as building more and larger impoundments and increased water abstraction, will compound the direct effects of climate change in freshwater ecosystems. [4.3.3.3, 4.3.4.5**] There is *very high confidence* that the use of the terrestrial biosphere in climate mitigation actions, such as through introduction of fast-growing tree species for carbon sequestration or the conversion of forest to biofuel plantations, may lead to negative impacts on ecosystems and biodiversity.** The land use scenario accompanying the mitigation scenario RCP2.6, intended to avoid 2°C global warming, features large expansion of biofuel production, displacing natural forest cover. [4.2.4.1]

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in the Working Group II report chapters 3 (Freshwater resources and their management; Kundzewicz *et al.*, 2007) and 4 (Ecosystems, their properties, goods and services; Fischlin *et al.*, 2007). Together they found that 'Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases'. Although circumstantial evidence was offered that anthropogenic climate change was a cause of the observed changes, it was not possible to attribute a relative proportion of the changes to this cause with any confidence. An important finding was that 20-30% of the plant and animal species that had been assessed to that time were considered *likely* to be at increased risk of extinction if the global average temperature increases exceeded 2-3°C. Fischlin *et al.* (2007) also stated that substantial changes in structure and functioning of ecosystems (terrestrial, marine and other aquatic) are *very likely* under a warming of more than 2-3°C above pre-industrial levels. No timescale was associated with these findings. The report noted that vulnerability to climate change could be exacerbated by the presence of other stresses, such as pollution.

4.2 A Dynamic and Inclusive View of Ecosystems

Ecologists no longer view ecosystems as inherently unchanging unless perturbed by an externally originating disturbance (Hastings, 2004). A growing body of both theory and observation (Scheffer, 2009) supports the emerging view that most ecosystems vary substantively over time in the relative magnitude of their components and fluxes, even under a relatively constant environment. Furthermore, attempts to restrict this intrinsic variation - or that resulting from imposed disturbances - are frequently futile, and may damage the capacity of the ecosystem to adapt to changing environments (Folke *et al.*, 2004). Contemporary treatments of ecosystems treat humans as an integral part of the system, rather than as an external perturbation to the natural state without any feedback to the human system itself (Gunderson and Holling, 2001). The emerging view is of relatively tightly coupled social-ecological systems, which means that their joint dynamics are governed not only by biophysical processes such as energy flows, material cycles, competition and predation, but also by social processes such as economics, politics, culture and individual preferences (Walker and Salt, 2006).

4.2.1. Ecosystems as Adaptive Entities

There is increasing focus on how ecosystems behave in the vicinity of their environmental limits, rather than solely on their behavior near the middle of their domain of their inferred preferred state (Scheffer *et al.*, 2009). The notion of thresholds has become a prominent ecological and political concern (Lenton *et al.*, 2008; Knapp et al 2008, Scheffer *et al.*, 2009; Leadley *et al.*, 2010). Some thresholds reflect a human preference that the ecosystem stays within certain bounds. Others reflect fundamental biophysical properties, for instance the thawing of frozen soils (see Box 4-4); or the physiological tolerance limits of constituent species. A third category of threshold relates to system dynamics under externally-driven change: the point at which the net effect of all the positive and negative feedback loops regulating the ecosystem is positive, causing a small perturbation to become amplified sufficiently to lead to a change in ecosystem state, from which it will not spontaneously return in the short term. The new state will typically exhibit different dynamics, mean composition, sensitivity to environmental drivers and flows of ecosystem services relative to the prior state. This type of threshold is called a tipping point (see glossary).

The early detection and prediction of ecosystem thresholds, particularly tipping points, is an area of active research. There are indications (Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold.In practice, such signals may not be detectable against background noise and uncertainty until it is too late to avoid the threshold (Biggs *et al.*, 2009). The dynamics of ecosystems are complex and our present level of knowledge is often inadequate to predict an ecosystem outcome with confidence, even if the future climate was precisely known.

The term 'resilience'(see glossary) has attracted a range of meanings in different disciplines. In ecology it is used both in the sense of 'a measure of the ability of these systems to absorb changes of state variables, driving variables

and parameters, and still persist' (Holling, 1973), and also in a broader sense of being able to adapt to change, without necessarily remaining within the same dynamical range (Walker *et al.*, 2004) and has been applied in the context of climate change (e.g. Morecroft *et al.*, 2012). One source of such adaptability is evolution within the populations of organisms making up the ecosystem. Natural selection operates on genetic variability against those individuals less able to survive, compete and successfully reproduce in the altered environment, leading to a shift, over generations, in the tolerance range of the population. Organisms also typically exhibit physiological, developmental or behavioral plasticity, within limits, that does not require genetic change. A particular case occurs when humans in the ecosystem use learning and technology to alter how they interact with the system. A third form of adaptation occurs when the configuration and functional form of interactions within an ecosystem change, in some cases leading to a new stable state (www.regimeshifts.org). It occurs when the abundance of one or more species are greatly altered or are replaced by other species with similar functional attributes. In the extreme, this would constitute a change in ecosystem type.

Field observations over the past century in numerous locations in boreal, temperate and tropical ecosystems have detected shifts of plant species at the biome level upwards in elevation and to higher latitudes (Gonzalez *et al.*, 2010). These shifts have been formally or informally attributed to climate change ([INSERT TABLE 4-1 HERE Table 4-1, Figure 4-1). Projections of potential future vegetation indicate substantial susceptibility of ecosystems to biome shifts (Warszawski *et al*, submitted; Figure 4-2, Box 4-3, Box 4-4).

[INSERT TABLE 4-1 HERE
Table 4-1: Biome shifts from 1700 to the present from published field research that examined trends over periods > 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.* (2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). Biomes (and abbreviations), from poles to equator: tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate shrubland (TS), tropical grassland (RG), tropical woodland (RW). Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. * rate significant at $P \leq 0.05$).]

[INSERT FIGURE 4-1 HERE
Figure 4-1: Biome shifts from 1700 to the present at sites in Table 4-1, derived from Gonzalez *et al.* (2010). Temperature change is the rate from linear least squares regression of 1901-2002 temperatures (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). Numbers refer to the sites in Table 4-1. Arrows indicate general direction of shifts.]

[INSERT FIGURE 4-2 HERE
Figure 4-2: Fraction of land surface at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems models, global climate models and RCPs. The colors represent the different ecosystems models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window cente4red on that year. The median in each bin is denoted by a black horizontal line. The grey boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points; the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. Right: Fraction of global land surface subject to severe ecosystem change as a function of global mean temperature (left panels) and time (right panels) for the JeDi (upper) and JULES (lower) dynamic global vegetation model driven by the HadGEM2-ES global climate model. The colors represent the different RCPs used to drive the climate model. Good agreement of results at different levels of global warming demonstrates that results are independent of the emissions scenario. (Reproduced from Warszawski *et al.*, submitted)]

4.2.2. What the Paleoecological Record Can and Cannot Tell Us

Paleoclimatic observations and modelling indicate that the Earth's climate has always changed on a wide range of time-scales. In many cases, particularly over the last million years, it has changed in ways that are well-understood in terms of both patterns and causes, (Jansen *et al.*, 2007; IPCC AR5 WGI Chapter 5). Independent paleoecological records demonstrate with *high confidence (robust evidence, high agreement)* that the planet's biota (both terrestrial and aquatic), carbon cycle and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as projected future mid- to high-end change (e.g., MacDonald *et al.*, 2008; Claussen, 2009; Arneth *et al.*, 2010; Willis and MacDonald, 2011; Dawson *et al.*, 2011). Excellent examples of past large climate change events that drove large ecological change include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, ca. 443 Ma, the Devonian, ca. 359 Ma, the Permian, ca. 251 Ma, the Triassic, ca. 200 Ma, and the Cretaceous, ca. 65 Ma; Barnosky *et al.*, 2011). Major ecological change was also driven by climate change during the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing *et al.*, 2005; Jaramillo *et al.*, 2010), the early Eocene Climatic Optimum (EECO, 53-50 Ma; Woodburne *et al.*, 2009), the Pliocene (5.3 to 2.6 Ma; Haywood and Valdes, 2006; Haywood *et al.*, 2011), and the Last Glacial Maximum (LGM; 21 ka) to Holocene (11 ka) transition (MacDonald *et al.*, 2008; Clark *et al.*, 2009; Gill *et al.*, 2009; Williams *et al.*, 2010b; Prentice *et al.*, 2011; Daniau *et al.*, 2012). The paleoecological record thus provides *high confidence (robust evidence, high agreement)* that large climate change, such as that projected for the 21st century, can result in large ecological changes, including large scale biome shifts, reshuffling of communities and, potentially, species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7-12.9 ka) provides a relatively recent analogy for climate change at a rate of a speed that approaches that projected for the 21st century (Alley *et al.*, 2003; Steffensen *et al.*, 2008). Ecosystems and species responded rapidly during this period by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by humans activities (Gill *et al.*, 2009; Dawson *et al.*, 2011). In some regions, species became locally or regionally extinct, but there is no evidence for climate-driven large-scale extinctions during this period of rapid climate change (Botkin *et al.*, 2007; Willis *et al.*, 2010c), except for a small number of plant species (Jackson and Weng, 1999; Birks and Willis, 2008). However, these climate excursions differ from those projected for the future because they were regional rather than global; may have only regionally exceeded rates of warming projected for the future; and started from a baseline substantially colder than present (Alley *et al.*, 2003). The mid-Holocene around ca. 6 ka provides a very recent example of the effects of modest climate change, because regional warming during this period (ca. 0.5-1.5°C above pre-industrial temperatures in some regions) was the same order of magnitude as the warming the Earth has experienced over the last century. Ecological effects were small compared to periods with larger climate excursions, but even this small degree of warming was characterized by frequent fires in a drier Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrin *et al.*, 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Adamik and Kral, 2008), and large-scale migration of Boreal forest into a warmer tundra (Jackson and Overpeck, 2000). Past climate change, even more modest than mid-range projected future change, has also clearly impacted inland water systems (e.g., Smol and Douglas, 2007b; Battarbee *et al.*, 2009; Beilman *et al.*, 2009). However, there are no exact analogues for future climate change: none of the well-studied past periods of large climate change involved simultaneously the rates, magnitude and spatial scale of climate change projected for the next century and beyond (Jansen *et al.*, 2007; Schulte *et al.*, 2010; IPCC AR5 Chapter 5). Direct analogy with the paleoecological record is also unwarranted because future climate change will interact with other global changes such as land-use change, invasive species, pollution and overexploitation of natural resources (Pereira *et al.*, 2010). There is *high confidence (robust evidence, high agreement)* that these interactions will also be important: the paleoecological record provides *medium confidence* (*medium evidence, high agreement*) that exploitation by humans helped drive many large mammal species to extinction during periods of climate change in past (Lorenzen *et al.*, 2011).

It has been demonstrated that state-of-the-art vegetation models are able to simulate much of the biome-level equilibrium response of terrestrial to large paleoclimate change (Prentice *et al.*, 1996; Salzmann *et al.*, 2008; Prentice *et al.*, 2011). These same types of models predict large changes in species ranges, ecosystem function and carbon storage when applied to 21st century climate change (Sitch *et al.*, 2008; Cheaib *et al.*, 2012). Thus, the paleoecological record, and models that have been tested against that record provide a coherent message that biomes

will move, species mixtures will change, novel new plant communities will emerge, and significant carbon changes will take place, all in response to changing and often novel future climates (Williams and Jackson, 2007; Williams *et al.*, 2007b; MacDonald, 2010; Prentice *et al.*, 2011; Willis and MacDonald, 2011); see Section 4.3.2.5 for more specific information on migration rates). As such, the paleoecological record and models provide *high confidence (robust evidence, high agreement)* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2 to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler *et al.*, 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Watrin *et al.*, 2009; Williams *et al.*, 2009; Mueller *et al.*, 2009a; Harrison and Goni, 2010), and this same record thus provides a critical model evaluation opportunity that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Marlon *et al.*, 2009; Jackson *et al.*, 2009; Williams *et al.*, 2009; Daniau *et al.*, 2010; Dawson *et al.*, 2011).

The paleoeclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (IPCC AR5 Chapter 12), but even these slower changes often drove surprisingly abrupt, or non-linear, regional change in terrestrial and aquatic systems (e.g., Harrison and Goni, 2010; Williams *et al.*, 2011), as did even slower orbitally-driven change during the most recent Holocene interglacial (e.g., Booth *et al.*, 2005; Kropelin *et al.*, 2008; Williams *et al.*, 2010b; Williams *et al.*, 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for more global rapid changes listed at the start of this section. State-of-the-art climate and Earth system models are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011) and thus there is *medium confidence* (*medium evidence, medium agreement*) that these models may not capture some aspects of future climate change and associated ecosystem impacts (Leadley *et al.*, 2010).

4.2.3. Landscapes and Social-Ecological Systems

Ecosystems do not exist in isolation from one another or from human systems. Landscapes, which consist of multiple interacting ecosystems, all experience some degree of interaction with people. The responses of terrestrial and freshwater ecosystems to climate change are therefore mediated by human activities at a range of spatial and temporal scales, and to varying degrees. Together, the social and ecological elements form a linked system (a ‘social-ecological system, SES) in which the degree of coupling can range from very close to slight (Berkes *et al.*, 2003).

4.2.4. Multiple Stressors and the Role of Climate Change

While isolated effects of the main drivers of global change (e.g. climate change, habitat loss, chemical pollution and biological invasions) are increasingly well documented (Millennium Ecosystem Assessment, 2005b; Settele *et al.*, 2010a) there is much less knowledge about their consequences when acting in combination. Multiple stressors can act in a non-additive way (Settele *et al.*, 2010b; Shaw *et al.*, 2002; Larsen *et al.*, 2011), potentially invalidating findings and interventions based on single-factor analysis. In a multifactorial climate change experiment Larsen *et al.*, 2011), demonstrated that non-additive interactions among the climate factors were frequent but most often antagonistic leading to smaller effects than predicted from the single factor effects. Leuzinger *et al.*, (2011) and Dieleman *et al.*, (2012) have synthesized such multifactor interactions and demonstrated that in general, the effect size appears to be reduced when more factors are involved. Leuzinger *et al.* (2011) further showed that models tend to show the opposite trend.

Climatic and non-climatic drivers of ecosystem change must be distinguished if the joint and separate attribution of changes to their causes is to be performed – of paramount importance if the processes of change are to be understood and future changes predicted. Within this section we elaborate on drivers and stressors which often act in concert with climate change, ranging from a high degree of relatedness to climate change (rising CO_2; tropospheric ozone; total, diffuse and UV radiation), over intermediate (land-use change) to low degrees of relatedness (invasive species and N deposition).

4.2.4.1. Land-Use and Cover Change (LUCC)

Land use and land cover continues to change worldwide. In tropical and subtropical areas of Asia, Africa, Oceania and South America, the most widespread land-use changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures and commercial plantations, followed by conversion of grasslands and pastures to annual agriculture. Afforestation at the expense of agricultural lands is more frequent in Europe (Rounsevell and Reay, 2009; Schwaiger and Bird, 2010; Miyake *et al.*, 2012) and loss of agricultural land to urban settlements is common in both the developed and developing world. LUCC is both a cause and consequence of climate change. The underlying drivers of LUCC include rising demand for food, fiber and bioenergy, and changes in lifestyle and technologies – some of which are also drivers of climate change. In the future climate change is projected to become a major driver of land cover change and ecosystem functioning, with more than a quarter of the land surface projected to be at risk of severe ecosystem change at global warming of 4°C or above (Figure 4-2). Land cover change can also be caused by change in non-climate environmental drivers such as nutrient loading, pollution and disturbance regimes.

The cause-and-effect entanglement of climate change and LUCC make attribution of consequences to one or the other very difficult. In 13 of the 24 regional land use studies reviewed for this chapter, local-to-regional climate change was at least partly attributed to LUCC, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Tseng and Chen, 2008; Cui and Graf, 2009; Li *et al.*, 2009; McAlpine *et al.*, 2009; Zhang *et al.*, 2009; Fall *et al.*, 2010; Graiprab *et al.*, 2010; Jin *et al.*, 2010; Mishra *et al.*, 2010; Schwaiger and Bird, 2010; Wu *et al.*, 2010; Gao and Liu, 2011; Carmo *et al.*, 2012. No climate effects attributed: Suarez *et al.*, 1999, Saurral *et al.*, 2008; SuFen *et al.*, 2008; Cochrane and Barber, 2009; Jia *et al.*, 2009a; Rounsevell and Reay, 2009; Martin *et al.*, 2010, Wiley *et al.*, 2010; Clavero *et al.*, 2011; Dai *et al.*, 2011; Viglizzo *et al.*, 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC contributes to climate change through changes in the sources or sinks of greenhouse gases and through changes in the absorption of solar energy by the land surface. These factors can have opposite effects and operate at different scales. For instance, conversion of forest to non-forest generally releases carbon dioxide from biomass and soils to the atmosphere, causing warming globally; but also often results in an increase in seasonally-averaged albedo, causing cooling locally and globally (Davin *et al.*, 2007), and a decrease in transpiration, causing warming locally but not globally. Four out of five global climate models suggested local cooling effects following forest conversion to croplands and pastures (Pitman *et al.*, 2009). Equilibrium experiments with the GDFL climate model (Findell *et al.*, 2007) concluded that the land-use change driven climatic impacts *not* mediated by greenhouse gases were generally minor, but significant in a few regions (Eastern Europe, Northern India, and Eastern China). More substantial global effects were projected by van der Molen *et al.* (2011) who found little temperature response to change from forests to pasture or crops in the tropics, increasing towards the Northern Hemisphere mid-latitudes. In high latitudes, changes in snow cover exposure and duration contribute to the albedo increase following forest clearing (Mishra *et al.*, 2010, Levis, 2010).

Afforestation programs are often recommended to promote carbon sequestration (e.g. Fiorese and Guariso, 2013; Singh *et al.*, 2013) but over the long term afforestation may lead to a slight net global warming when the albedo increase effect neutralizes the carbon uptake effect (Schwaiger and Bird, 2010). Wickham *et al.*, (2012) found significant positive slopes in regressions of average annual surface temperatures versus the proportion of forest and argue that the value of temperate afforestation as a potential climate change mitigation strategy is unclear. Changes in albedo, other biophysical effects and some indirect greenhouse effects (such as changes in soil erosion), are not

currently included in the formal rules for accounting for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum *et al.*, 2012).

The reported effects on precipitation of conversion of forest to pastures and crops vary. Many studies report rainfall decreases, soil moisture decreases and changes in rainfall pattern (e.g. Nepstad *et al.*, 2008; McAlpine *et al.*, 2009; Mendelsohn and Dinar, 2009; Eliseev and Mokhov, 2011). In some cases forest clearing has been reported to enhance local rainfall. Garcia-Carreras and Parker (2011) suggest that enhanced local precipitation can occur over deforested patches due to breezes between forest and cropland. Enhanced rainfall over vegetation boundaries has been shown to occur both in the Amazon (e.g. Knox *et al.*, 2011) and in West Africa (e.g. Garcia-Carreras *et al.*, 2010) as a result of mesoscale processes that are currently not resolved in General Circulation Models.

In China, Han *et al.*, (2012) compared historical data from 244 weather stations predominantly surrounded by cultivated land and 195 stations surrounded by with >70% natural cover. They observed a greater decrease in potential evaporation at stations with significant agricultural influence. In arid and semi-arid regions this was associated with a decrease in wind speed, increase in relative humidity and increase in air temperature compared with natural stations; while in humid and sub-humid regions it was associated with increased wind speed and decreased solar radiation.

Several assessments conclude that LUCC, acting through habitat loss and fragmentation, is the largest cause of contemporary terrestrial and freshwater biodiversity loss, with climate change becoming an increasingly important factor later in the 21st century (Millennium Ecosystem Assessment, 2005a; http://www.cbd.int/gbo3/).

_____ START BOX 4-1 HERE _____

Box 4-1. Future Land Use Pathways and Their Uncertainties

Assessment of climate change effects on terrestrial and inland freshwater ecosystems is incomplete in the absence of information on the direct impacts of people on these systems through land use. The world is undergoing important shifts in land-use patterns. Growth in demand for food, feed, fiber, and fuel has accelerated in recent years, placing new pressures on terrestrial and freshwater ecosystems and outpacing the growth in supply. The principal driver of this acceleration in demand is the rate at which per capita consumption is growing in emerging economies (Tilman *et al.*, 2011). Policy shifts in OECD countries favoring the expansion of biofuel production have contributed to this acceleration (Lapola *et al.*, 2010; Searchinger *et al.*, 2008; Miyake *et al.*, 2012). Growth in demand that outpaces growth in supply, climate-related crop failure (Lobell *et al.*, 2011), declines in the growth of agricultural productivity (Ray *et al.*, 2012) and possibly a shortage of arable land that is not already under cultivation, especially in the temperate zone (Lambin and Meyfroidt, 2011) are all contributing to a rise in commodity prices that may persist through 2020 (OECD/FAO, 2010) and growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa.

Emerging economies start from a relatively low per capita consumption base. The growth of these economies will therefore play an important role in future land use trends. Deforestation in developing countries is now correlated with the export of agricultural commodities (DeFries *et al.*, 2010), providing an early sign of the growing role of agricultural trade with emerging economies as a driver of land-use change. The trajectory of future growth in demand for land- and freshwater-based production remains uncertain, since it depends on economic trends and policies, which are themselves dependent upon complex political and social processes. One of the uncertainties about future land use trends is climate policy. Deforestation rates in the Brazilian Amazon declined 76% (as of 2012) below its ten-year average as a result of policy and market signals (Soares-Filho *et al.*, 2010); this single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad *et al.*, in press).

These land use trends and the global land cover patterns that they promote have been simulated and mapped within a global grid as input to the Regional Concentration Pathways (RCPs) in preparation for the IPCC AR5. The 4 main RCPs used for future climate projections are accompanied by spatially-explicit future land use scenarios consistent with the emissions scenario and the associated socio-economic scenario (Hurtt *et al.*, 2011) generated by Integrated

Assessment Models using simple methodologies intended to capture the main processes at continental and global scales.

[INSERT TABLE 4-2 HERE
Table 4-2: Summary of drivers and outcomes of land use / cover scenarios associated with Representative Concentration Pathways (Hurtt et al., 2011).]

In the RCPs, land cover change is driven by a number of socioeconomic drivers, including climate policy. The nature of climate policy effects on land use differs between RCPs, with some climate mitigation policy scenarios including conservation of primary vegetation (natural, mature ecosystems) as carbon sinks while others included replacement of primary vegetation with biomass and / or biofuel plantations. The extent to which primary vegetation is replaced by secondary vegetation, crops or pasture also varies between the RCPs (Figure 4-3), but there is no simple linear relationship between the extent of vegetation change and the level of total radiative forcing arising from all sources. Larger reductions in primary vegetation cover are seen in RCP8.5 (the highest emissions scenario) due to a general absence of pro-active measures to control land cover change, but large reductions were also seen in RCP2.6 (an aggressive mitigation scenario with low emissions) due to widespread conversion of land to biomass and biofuel crops coupled with carbon capture and storage. Smaller reductions were seen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest or regrowth of secondary forest as a mitigation measure. Hence both the highest and lowest emissions scenarios were associated with greater extents of land cover change.

[INSERT FIGURE 4-3 HERE
Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005 (KleinGoldewijk, 2001), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt *et al.*, 2011).]

Spatial patterns of the future land cover change in all RCPs were largely similar to patterns of historical change (Figure 4-4) as most future change is projected to be a continuation of past change. By definition, primary vegetation cover cannot increase on the timescales considered here, so in scenarios where cropland and pasture are projected to decrease, these are replaced with secondary vegetation. Both tropical and boreal forest regions are projected to undergo declining primary forest cover in all 4 RCPs, but in RCP6.0 total forest area remains approximately constant.

[INSERT FIGURE 4-4 HERE
Figure 4-4: Fractional cover of primary vegetation at 1850, 2005 based on satellite data and historical reconstructions (KleinGoldewijk, 2001) and at 2100 in scenarios associated with the RCPs (Hurtt *et al.*, 2011).]

_____ END BOX 4-1 HERE _____

4.2.4.2. Nitrogen Deposition

The global nitrogen (N) cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Sutton *et al.*, 2011). Human activities currently transform 160 TgN/year of nitrogen gas in the atmosphere into reactive forms of N that can be readily used by plants and microorganisms in land and in the ocean (Galloway *et al.*, 2008). This is close to the pre-industrial global flux of about 255 TgN/year from all natural sources. The human-caused flow from land to the coastal oceans in rivers is about 50 TgN/y, additional to the estimated natural flux of 30 TgN/year (Galloway *et al.*, 2008). Many of the sources of additional reactive nitrogen share root causes with changes in the carbon cycle - such as increased use of fossil fuels and expansion and intensification of global agriculture - so N deposition, rising CO_2 concentrations and warming are increasing together at global scales (Steffen *et al.*, 2011). This large addition of reactive N into the biosphere can reinforce global warming (e.g., though emission of N_2O associated with fertilizer manufacture and application), or diminish warming (e.g., by increasing C storage in many terrestrial ecosystems). The balance of these effects is difficult to estimate (Erisman *et al.*, 2011; WG1 chapter 6; Hanson *et al.*, 2005). Regional trends in N fluxes differ substantially: N fertilizer use and N deposition are stable or declining in some regions, such as Western Europe; but

N deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in regions dominated by rapidly-growing emerging economies (Galloway *et al.*, 2008).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the dominance of a few nitrogen-loving plant species and loss of overall plant species richness at N deposition loads exceeding between 5 and 20 kgN/ha/year (Bobbink *et al.*, 2010; but see Stevens *et al.*, 2010a). N deposition is currently above these limits in much of Europe, eastern North America, and Southern Asia (Galloway *et al.*, 2008), including in many protected areas (Bleeker *et al.*, 2011). Experiments examining the interactive impacts of N deposition and elevated CO_2 or climate change on natural systems have increased in number since the AR4, but remain few (Rustad, 2008). Recent studies show that interactions between nitrogen and other global change factors are widespread, strong and complex (Thompson *et al.*, 2008; Langley and Megonigal, 2010; Gaudnik *et al.*, 2011; Hoover *et al.*, 2012; Eisenhauer *et al.*, 2012; but see Zavaleta *et al.*, 2003a for evidence of additive effects). For example, combinations of treatments mimicking future N deposition, elevated CO_2 concentrations and warming had larger negative impacts on pollinator populations than could be predicted from individual treatments (Hoover *et al.*, 2012). Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that N deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due expansion of agricultural lands (Alkemade *et al.*, 2009). Models that explicitly take into account interactive effects of climate change and N deposition on plant communities project that N deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid *et al.*, 2011).

The impacts of N deposition are often first manifested in freshwater ecosystems, since they collect and concentrate the excess N (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either N and P limited or both (Elser *et al.*, 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high quality water, recreational amenity and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of N and P is widespread in the lakes of the northern hemisphere (Bergstrom and Jansson, 2006). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser *et al.*, 2009).

Since the AR4 report there has been an increase in the number of studies using models, observations and experiments to understand and predict the interactive effects of N deposition, climate change and CO_2 on ecosystem function. Broadly, this research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Norby and Zak, 2011; Churkina *et al.*, 2010). For example, experiments, observations and models suggest that the observed increase in productivity and carbon storage in forests in many parts of the world is due to combinations of N deposition, climate change, fertilization effects of rising CO_2, and forest management (Magnani *et al.*, 2007; Huang *et al.*, 2007; Pan *et al.*, 2009; Churkina *et al.*, 2010; Bontemps *et al.*, 2011; Bellassen *et al.*, 2011; de Vries and Posch, 2011; Eastaugh *et al.*, 2011; Norby and Zak, 2011; Shanin *et al.*, 2011; Lu *et al.*, 2012). Despite difficulties in quantifying the relative contributions of these factors and their interactions, it appears that the effects of N deposition and rising CO_2 have generally dominated to date in much of the Northern hemisphere, however, the direct effects of rising temperature and changes in precipitation are may exceed N and CO_2 as key drivers of ecosystem primary productivity in a few decades time. On the other hand, experiments in grasslands show that plant productivity is increased more by N addition (within the projected range for this century) than by elevated CO_2, also within its projected range; and that N effects increase with increasing precipitation (Lee *et al.*, 2010). In contrast to forests and temperate grasslands, N deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens *et al.*, 2011). The interactions between N deposition and climate change remain difficult to understand and predict (Ma *et al.*, 2011; Menge and Field, 2007), in part due to shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled C, N and P cycles (Menge and Field, 2007; Niboyet *et al.*, 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to terrestrial ecosystems) has been rising over the past 160 years (Horowitz, 2006; Oltmans *et al.*, 2006; Cooper *et al.*, 2010). This is due to increasing anthropogenic emissions of gases which react in the atmosphere to form ozone (Denman *et al.*, 2007), but is also partly due to the increased mixing of stratospheric ozone into the troposphere as a result of climate change (Hegglin and Shepherd, 2009). The key ozone-precursor gases are volatile organic compounds (VOC) and oxides of nitrogen (NO_x). Intercontinenal transport of these precursors is contributing to rising global background ozone concentrations, including in regions where local emissions are decreasing (Dentener *et al.*, 2010).

Negative effects of the current levels of ozone have been widely documented (Mills *et al.*, 2011). A meta-analysis of over 300 articles addressing the effect of ozone on tree growth (Wittig *et al.*, 2009) - largely focussed on northern-hemisphere temperate and boreal species - concluded that current levels of tropospheric ozone are suppressing growth by 7% relative to pre-industrial levels. Modelling studies extrapolating measured dose-response functions suggest a 5 to 30% contemporary reduction in Net Primary Productivity (NPP) worldwide (Sitch *et al.*, 2007) and 1-16% in temperate forests (Ainsworth *et al.*, 2012).

The mechanisms by which ozone affects plant growth are now better known (Hayes *et al.*, 2007; Ainsworth *et al.*, 2012). Chronic exposure to ozone at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008) although some evidence also suggests ozone exposure may increase stomatal conductance (Wilkinson and Davies, 2010). For the species studied, carbon assimilation rates are generally reduced and respiration increases, leaf area is reduced and leaf senescence accelerated - all leading to a reduction in NPP and biomass accumulation. Gymnosperms are less sensitive than angiosperms. In a modeling study, lower stomatal conductance due to ozone exposure increased river runoff by reducing the loss of soil moisture through transpiration (Huntingford *et al.*, 2011), although studies that measured runoff are contradictory on this issue (Wittig *et al.*, 2007; McLaughlin *et al.*, 2007; Mills *et al.*, 2009; Huntingford *et al.*, 2011).

A modeling study (Sitch *et al.*, 2007) suggests that the negative effects of rising O_3 on plant productivity could offset 17% of the projected increase in global carbon storage due to increasing CO_2 concentrations, but the possible interactive effects between CO_2 and O_3 are poorly understood (The Royal Society, 2008). Reduced stomatal conductance widely observed under elevated CO_2 should help protect plants from ozone damage. Some chamber experiments (Bernacchi *et al.*, 2006) and model studies (Klingberg *et al.*, 2011) suggest this to be the case. The one plot-scale FACE study of CO_2 and O_3 interactions in a temperate forest (Karnosky *et al.*, 2005; Hofmockel *et al.*, 2011) suggests that the effects of O_3 and CO_2 are not independent and may partly compensate for one another.

There is genotypic variation in sensitivity to O_3 (Ainsworth *et al.*, 2012). Other than changing cultivars or species, there is not believed to be much scope for management actions promoting adaptation to higher levels of O_3 (Teixiera *et al.*, 2011; Wilkinson and Davies, 2010). Research into developing ozone resistant varieties and/or chemical protectants against damage may provide management options in the future (Ainsworth *et al.*, 2012, Wilkinson and Davies, 2010).

4.2.4.4. Rising CO_2

The effects of rising CO_2 on the global carbon cycle are discussed in chapter 6 of the WG1 report [Box 6-3, in the SOD]. The discussion here is focused on impacts on terrestrial ecosystems and inland water systems.

Since AR4, investigation of elevated CO_2 effects on plants and ecosystems has focused mainly on Free Air CO_2 Enrichment (FACE) techniques, which have now been in use for approximately 20 years (Leakey *et al.*, 2009) and are considered more realistic than earlier approaches using enclosed chambers because plant community and atmospheric interactions and below-ground conditions are more like those of natural systems. C3 plant species, which includes nearly all tree species, show a general increase in photosynthesis under elevated CO_2, although the response varies between species. Although FACE experiments indicate lower responses of crop yields to elevated

CO_2 than chamber studies, FACE experiments initially suggested greater biomass production of trees (Leakey *et al.*, 2009). But newer results from older stands show that different system respond differently, and only at the Duke forest, a loblolly pine (*Pinus taeda*) stand in North Carolina has biomass accumulation been enhanced several years after canopy closure on rather nutrient poor soils (McCarthy *et al.*, 2010). At most other tree FACE experiments, most of the additional carbon gain has been invested into below-ground pools with short residence time, such as fine roots (Körner *et al.*, 2005; Finzi *et al.*, 2007), and the initial positive response of NPP at the Oak Ridge experiment with sweetgum (*Liquidambar styraciflua*) has disappeared due to progressive nitrogen limitation with stand development (Norby *et al.*, 2010). Acclimation ("down-regulation") occurs under long-term exposure, leading to cessation of effects in some studies (Norby and Zak, 2011) but with on-going stimulation of photosynthetic carbon assimilation due to elevated CO_2 persists at a level of 19 to 46% for approximately 600 ppm CO_2 relative to 370 ppm reported elsewhere (Leakey *et al.*, 2009). Kongstad *et al.* (2012 did not find such increases for a temperate heathland. Paleo records over the Late Quaternary also indicate effects of CO_2 at the ecosystem scale across the globe (Prentice and Harrison, 2009). Generally, nitrogen use efficiency and dark respiration are also both increased under higher CO_2 (Leakey *et al.*, 2009), but in some tree FACE experiments, productivity increases as a result of enhanced CO_2 were sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi *et al.*, 2007). Transpiration is decreased due to reduced opening of stomatal apertures which does not acclimate to higher CO_2 in the medium term, *i.e.* the scale of several years leading to greater water use efficiency (Leuzinger and Körner, 2010; Leakey *et al.*, 2009; De Kauwe *et al.*, 2013) – this is corroborated by additional evidence from studies of stable carbon isotopes (Barbosa *et al.*, 2010; Koehler *et al.*, 2010; Silva *et al.*, 2010; Maseyk *et al.*, 2011). C4 plant species, which includes most tropical grasses and some crops, undergo photosynthesis via a different biochemical pathway which is not directly affected by elevated CO_2. However, CO_2 rise generally increases water use efficiency of C4 plants which can exert indirect effects on growth (Leakey *et al.*, 2009). Experiments have also shown that elevated CO_2 has potential to stimulate root growth (e.g. Finzi *et al.*, 2007; McMurtrie *et al.*, 2012), mineralisation of soil organic matter (Drake *et al.*, 2011; Carney *et al.*, 2007, but see Finzi *et al.*, 2007) and soil microbial communities (Carney *et al.*, 2007), although Norby and Zak (2011) suggests that elevated CO_2 effects on the microbial community structure are minor. Impacts of CO_2 physiological forcing may extend beyond the organisms themselves – increased water use efficiency may significantly influence hydrological impacts (see Box CC-VW).

Elevated CO_2 can assist in maintaining resilience of individual species against other stresses, such as high temperature, drought and ozone, as ozone exposure decreases with lower stomatal conductance (Sitch *et al.*, 2007). It is also suggested that faster growth rates under higher CO_2 can allow woody plants to become tall enough to withstand ground fires, and hence alter the fire/vegetation regime in rangelands (Bond and Midgley, 2001; Scheiter and Higgins, 2009) It is also suggested that differential species responses to elevated CO_2 are altering competition (Dawes *et al.*, 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Potvin *et al.*, 2007; Lewis *et al.*, 2009a).

The interactive effects of elevated CO_2 and other global changes (such as climate change, nitrogen deposition and biodiversity loss) on ecosystem function are extremely complex and as yet poorly predictable (Potvin *et al.*, 2007). For example, in one ten-year temperate grassland experiment in Minnesota, elevated CO_2 halved the loss of species richness due to nitrogen addition (Reich, 2009), whereas no such change was reported for a similar experiment in annual grassland on serpentine soils in California (Zavaleta *et al.*, 2003a) or an alpine grassland in France (Bloor *et al.*, 2010) or a Danish heathland ecosystem (Kongstad *et al.*, 2012). Some of the mechanisms of community and production changes under multi-factor forcing may be mediated through changes in plant litter quality, although in the temperate grassland experiment described above the changes in litter decomposition rates were less marked than the changes in the chemical composition of tissues (Knops *et al.*, 2007). Hyvönen *et al.* (2007) review the combined effects of elevated CO_2, temperature, nitrogen deposition and management on carbon sequestration in temperate and boreal forests and conclude that findings extrapolated from experiments that only consider one of these factors in isolation can be misleading. Since FACE experiments either examine CO_2 effects in isolation, or in conjunction with a very limited set of imposed climate changes such as elevated temperature, the extent to which CO_2 responses are affected by a range of temperature changes or other climatic or environmental factors remains poorly studied. A further, broader analysis supports this, and further suggests that the magnitude of CO_2 effects decreases as the scale of study increases (Leuzinger *et al.*, 2011).

Inclusion of CO_2 effects can be a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change. For example, most CMIP3 climate models project a drying, warming trend in Amazonia, and this leads to widespread forest loss being simulated under most climate projections in a model that ignores CO_2 effects (Salazar *et al.*, 2007). However, when CO_2 effects are included, the same model projects forest loss under fewer climate projections (Lapola *et al.*, 2009). The current generation of dynamic global vegetation models (DGVMs; (Sitch *et al.*, 2008), which includes those used within the CMIP5 Earth System Models, uses formulations based on experimental work that pre-dates FACE experiments (e.g., Farquhar *et al.*, 1980; Collatz *et al.*, 1992). However, the DGVMs simulate present-day global carbon budgets that agree with those inferred from observations such as the atmospheric CO_2 record (Sitch *et al.*, 2008).

The effect of CO_2 on plant physiology independent of its role as a greenhouse gas has implications for the definition of "dangerous climate change" in terms of levels of global mean temperature rise, and for the use of "CO_2 equivalent" metrics for comparing different greenhouse gases. Aside from uncertainties in the response to a given change in CO_2 concentration, the relative importance of radiative forcing and "CO_2 physiological forcing" depend on uncertainties in the response of global climate to radiative forcing and also on the relative proportions of CO_2 and other greenhouse gases (Betts *et al.*, 2012). The impacts of, for example, a 2°C rise in global mean temperature may have a very different net impact on ecosystems depending on the change in CO_2 concentration accompanying this rise. A high climate sensitivity and/or a higher proportion of non-CO_2 GHGs would imply a relatively low CO_2 rise at 2°C global warming, so the offsetting effects of CO_2 fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO_2 GHGs. Similarly, inertia in the climate system means that warming would be expected to continue for many decades after stabilisation of GHG concentrations, so the relative contribution of CO_2 physiological effects would diminish over time. Comparison of the effects of CO_2 with other GHGs in terms of the current radiative forcing-based metrics may therefore not be representative of the relative effects of different GHGs on ecosystems and hydrology (Huntingford *et al.*, 2011).

There remain still important limitations on understanding of CO_2 responses. Large-scale FACE experiments have still only been conducted for up to two locations for any particular ecosystem type, and these are in temperate and boreal regions (e.g. Hickler *et al.*, 2008); there is currently no tropical FACE experiment. The scale of controlled experiments is limited to approximately $100m^2$, and extrapolation to larger scales may not be appropriate as other constraints may be important, for example large-scale atmospheric feedbacks (Körner *et al.*, 2007). Similarly, the limited size of FACE experiments means that influences on catchment-scale hydrology have not yet been studied experimentally. The majority of FACE experiments examine CO_2 concentrations of approximately 550 ppmv), which has been projected to be reached by the end of the 21st Century under a number of scenarios including RCP6.0 (van Vuuren *et al.*, 2011), whereas higher concentrations are projected under higher emissions scenarios; RCP8.5 reaches a CO_2 concentration of approximately 900 ppmv by 2100 (van Vuuren *et al.*, 2011). However, the basic physiology of photosynthesis suggest that CO_2 effects saturate at levels of approx. 700 ppmv (Long *et al.*, 2004). Moreover, FACE experiments impose a sudden increase of CO_2 concentration as opposed to the continuous rise measured in the present-day atmosphere. The extent to which photosynthesis and nitrogen and water use efficiency continue to increase with ongoing CO_2 rise therefore remains poorly-constrained. Overall, there is *medium confidence* (*much evidence, medium agreement*) that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate

4.2.4.5. Diffuse Versus Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and its distribution between direct and diffuse radiation. There are observed trends in diffuse and direct radiation in many parts of the world, usually in the direction of overall 'dimming'. Locally, direct radiation is reduced by up to 30 W m^{-2}, with an accompanying increase in diffuse radiation of up to 20 W m^{-2} (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are –3.3 and +0.9 W m^{-2}, respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis, (Knohl and Baldocchi, 2008; Kanniah *et al.*, 2012) and potentially could alter the hydrological balance and soil temperature. In a global model which included this process, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was

simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; but under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st Century (Mercado *et al.*, 2009). The influence of form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (Boucher *et al.*, in preparation) but is presently insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g. Walther *et al.*, 2009) and for particular areas, including mountain tops and polar regions (McDougall *et al.*, 2011; Chown *et al.*, 2012). The aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*; Brook, 2008; Burton *et al.*, 2010; McGeoch *et al.*, 2010; Simberloff *et al.*, 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson *et al.*, 2008; Bradley *et al.*, 2009; Britton *et al.*, 2010). The spread of alien species has several causes, including habitats made favorable by climate change (Walther *et al.*, 2009), deliberate species transfer and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread and survival of invasive species populations (Dukes *et al.*, 2009; Walther *et al.*, 2009; Bradley *et al.*, 2010; Huang *et al.*, 2011; Chown *et al.*, 2012). However, divergent alien species responses and local consequences are expected (e.g. Rahel and Olden, 2008; Frelich *et al.*, 2012; Haider *et al.*, 2012; West *et al.*, 2012). Invasive species compared to native species might have traits that favor their survival, reproduction and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium to high confidence*; Buswell *et al.*, 2011; Davidson *et al.*, 2011; Zerebecki and Sorte, 2011; van Kleunen *et al.*, 2010; Willis *et al.*, 2010a; Haider *et al.*, 2012; Matzek, 2012). Invasive plants tend to be more drought tolerant (Crous *et al.*, 2012; Matzek, 2012; Perry *et al.*, 2012), and on average have higher overall metabolic rates, foliar nitrogen concentrations and photosynthetic rates than their native counterparts (Leishman *et al.*, 2007).

Extreme climate events may provide opportunities for invasion by generating disturbances and resource pulses (Diez *et al.*, 2012). Current warming has already enabled many alien species, including plant, vertebrate, invertebrate and single cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther *et al.*, 2009; Smith *et al.*, 2012). Population declines and range contractions are however predicted for some invasive species in parts of their ranges (Bradley *et al.*, 2009; Bertelsmeier *et al.*, 2012; Sobek-Swant *et al.*, 2012; Taylor *et al.*, 2012;). The expansion of invasive species in some areas and contraction in others will contribute to community re-organisation and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*; e.g., Kiesecker, 2011; Britton *et al.*, 2010; Martinez, 2012; see also chapter 4.3.2.5.). For example, invasive grasses will probably be favored over native ones with increasing temperatures (Parker-Allie *et al.*, 2009; Chuine *et al.*, 2012; Sandel and Dangremond, 2012).

Benefits to biodiversity and society as a result of interactive effects of climate change and invasive species will be experienced in individual cases, such as increases in resources available to some threatened species (Caldow *et al.*, 2007), forest structural recovery (Bolte and Degen, 2010) and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific, and may be either positive or negative (Williams *et al.*, 2007a). Rising CO_2 levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010), but the effectiveness of invasive species management for sequestering carbon is uncertain and context specific (Peltzer *et al.*, 2010). Longer term, indirect effects of invasive species will be more important than direct, short-term effects, as a result of changes in soil carbon stocks and tree community composition (*low-medium confidence*; Peltzer *et al.*, 2010).

Threat syndromes are formed by synergistic interactions between climate change and invasive species, along with landscape change, habitat disturbance and human-facilitated breakdown of dispersal barriers (Brook, 2008; Angeler and Goedkoop, 2010; Bradley *et al.*, 2010; Winder *et al.*, 2011; Cahill *et al.*, 2013). Climate change and invasive

species change the risk and properties of fire, and the interaction is being reported more frequently as a direct result of higher temperatures and increased invasive plant biomass (*high confidence*; Abatzoglou and Kolden, 2011). In freshwater systems, alien species establishment and survival, species interactions and disease virulence will change as a result of changes in frequency of high-flow events, increasing water temperature, water properties and water demand (*medium confidence*; Schnitzler *et al.*, 2007; Rahel and Olden, 2008; Britton *et al.*, 2010).

A range of climate change-related variables (extreme events, changes in precipitation, temperature and CO_2) will continue to exacerbate the establishment and spread of pests, vectors and pathogens and negatively impact on crop production (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has led to the spread of many invasive insect species such as the mountain pine bark beetle and resulted in forest destruction (*high confidence*; Kurz *et al.*, 2008). The interactions between crop growth, climate change and pest dynamics are however complex to predict (West *et al.*, 2012). Management strategies may become less effective as a consequence of decoupling of biocontrol relationships and less effective mechanical control as biomass of invasive species increases (*low to medium confidence*; Hellmann *et al.*, 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Changes

Vulnerability of terrestrial ecosystems to climate change is defined as the combination of three things: the degree to which their climatic environment changes relative to conditions under which the ecosystem evolved; the sensitivity of ecosystem processes to the elements of climate undergoing change; and the degree to which the system (including its coupled social elements) can maintain its structure, composition and function in the presence of such change, either by tolerating the change or adapting to it. See WGII chapter 19 for a fuller discussion on vulnerability concepts.

4.3.1. The Importance of Changes in Disturbance Regime

The species composition at a given location is determined by three factors: the physiological tolerance of the various species that have access to the site in relation to the range of conditions experienced there; interactions with other species, including competitors, symbionts, predators, prey and pathogens; and the ability of species to reach the location in evolutionary or recent times. Occasional disturbances that relieve competition and create opportunities for establishment and success of less-dominant species are important in maintaining diversity. The average environmental conditions are often less of a determinant of species ranges than the extremes, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration, which are often defined as ‘disturbances’. The change in probability of such extremes is typically disproportionately larger than the change in the mean (see IPCC, 2012, but also Diffenbaugh *et al.*, 2005). Fire, floods and strong winds are all examples of biodiversity-sustaining events, provided that their frequency and intensity does not deviate greatly from the regime that prevailed at the location in evolutionary time; outside this range they have adapted to (Connell, 1978).

It is thought that widespread compositional shifts resulting from climate change in interaction with other factors will often be associated with changes in the disturbance regime, rather than physiological tolerance (Thonicke *et al.*, 2008). A ‘disturbance regime’ refers to the totality of different types of disturbance events in a system, each characterized by their probability-intensity function and other relevant attributes, such as their seasonal distribution. A corollary is that disturbance-related change is likely to abrupt rather than gradual.

Change in the fire disturbance regime, in particular, is emerging as a key, mechanism of terrestrial ecosystem change and an early indicator of change that has been detected and in some cases attributed to climate change (Westerling *et al.*, 2006; Littell *et al.*, 2009; Westerling *et al.*, 2011; Moritz *et al.*, 2012).

4.3.2. Evidence of Change in Ecosystems

This section highlights key indices of change in terrestrial and freshwater ecosystems over the recent past. It assesses the degree of confidence that change can be detected and the extent to which changes can be attributed to changes in climate (Figure 4-5). Confidence in detection of change is considered to be very high when there is high agreement between many independent studies, species, ecosystems or regions and where there is robust evidence that the changes over time are statistically significant (see WGII, Chapter 18; Mastrandrea *et al.*, 2010). Note that a slightly different definition than Chapter 18 for detection is used, because detection here is based solely on the presence of a temporal trend and does not attempt to distinguish natural from climate related variation. Confidence in attribution to climate change is very high when three criteria are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; time series of observations are sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. We have provided estimated levels of confidence even in cases where the capacity for detection or attribution capacity is low or very low, because changes in these ecosystem properties or processes could have large impacts on biodiversity or ecosystem services at regional to global scales. It is also important to account for the spatial distribution of climate change trends: for example, warming trends are very high in the Arctic and small or negative in parts of South America (Burrows *et al.*, 2011). Statements of confidence for detection and attribution are given without references, as detailed traceability is provided in the section 4.3.2, which follows this introduction.

Some of the subsections referred to include assessments of model-based projections of future change, but this analysis of detection and attribution does not cover projected changes in ecosystems. The absence of observed changes does not preclude high levels of confidence in projections of change in the future because 21st century climate change is projected to substantially exceed changes experienced over the last century, and because ecosystem responses to climate change may be non-linear and may appear after considerable time lags.

[INSERT FIGURE 4-5 HERE
Figure 4-5: Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels have are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010), and detection and attribution criteria outlined in Chapter 18. The points in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions.]

Phenology (see 4.3.2.1) - Since the AR4 report there has been a significant increase in the spatial, temporal and taxonomic coverage through ground-based phenological observation networks, data mining and remote sensing. These observations show that phenology, i.e., the timing of key life history events such as flowering in plants or nesting for birds, has shifted for many but not all species over the last several decades (*high confidence* due to *robust evidence* but only *moderate agreement* when examined across all species). Attribution of temporal shifts in phenology to qualitative expectations of responses due to global warming has given way to more refined analyses and models that account for regional differences in warming trends, urban heat island effects, confounding effects of other global change drivers, and non-linear responses of phenology to warming. These advances notwithstanding, attribution can only be made with *high confidence* because there are a wide range of confounding factors, a substantial fraction of species that have not responded in a predictable manner and discrepancies between phenological shifts in experiments vs. observations.

Primary Productivity (see 4.3.2.2) and Biomass and C Stocks (see 4.3.2.3) - Evidence has accumulated from a wide range of sources including eddy flux towers, inversion of atmospheric CO_2 concentrations, remote sensing and models that, once the effects of deforestation are accounted for, terrestrial ecosystems are currently net sinks for carbon over much of the Northern hemisphere and parts of the Southern hemisphere (*high confidence*). Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this but confounding factors such as N deposition, afforestation and land management make attribution of these trends to climate change difficult (*low confidence*). Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution.

Evapotranspiration (see 4.3.2.4) - Evapotranspiration is now being monitored at a variety of scales ranging from individual plants to large regions. A variety of studies suggest that evapotranspiration increased over the period 1970-1990, but there is substantial uncertainty in this estimate due to low agreement across studies leading to *low confidence* in detection of a trend. The trend of rising evapotranspiration from 1970-1990 has been attributed to global warming, and the absence of a continued trend in from the 1990s onward has been attributed to increased water stress. However, there is *low confidence* in these attributions because of the large number of confounding factors that influence transpiration including N deposition, land management and irrigation.

Species Distributions (see 4.3.2.5) - Depending on the species and species group, there are varying degrees of confidence in the detection of species range shifts and that these range shifts can be attributed to climate change. The number of species studied has considerably increased since the AR4 report as have the number of studies examining the mechanisms underlying range shifts. There is a wide range of evidence from models, field studies, and quantitative comparisons between observed and expected range shifts that some species and species groups, especially arthropods, have shifted their ranges significant distances (10s of km or more) over the last several decades (*high confidence*). Range shifts — that must be distinguished from shifts in community composition — in other key species groups such as plants have been much more difficult to detect, meaning there is only *medium confidence* in detection in range shifts when examined across all species groups. Range shifts in some species groups, e.g., arthropods, correlate well with warming over the last several decades and can be linked to changes in climate through understanding of mechanisms. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in attribution when examined across all species. An importance advance since the AR4 report is the recognition changes in climate over the last several decades have led to range shifts that are frequently not towards the poles or up in altitude due to many factors including interactions between warming, land use and changes in precipitation (*high confidence*).

Global Species Extinctions (see 4.3.2.5) - There is *high confidence* that global species extinctions are at or above the highest rates of species extinction in the fossil record, and *high confidence* that global extinctions have increased in some species groups, e.g., amphibians, over the last several decades. However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades. Only a small fraction of observed species extinctions have been attributed to climate change — most have been ascribed to invasive species, overexploitation, habitat loss or habitat modification. As such, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming given the small fraction of species for which global extinction has been ascribed to climate change and tenuous nature of most attributions. However, in the specific case of Central American amphibians, there is *medium evidence* that recent climate warming has contributed to extinctions and *medium confidence* in this attribution. There is *low agreement* among investigators concerning the importance of climate compared to other factors such as invasive disease and habitat loss.

Invasive and Alien Species (see 4.2.4.6) - There is *very high confidence* that species invasions are increasing over the last several decades. There is *high confidence* that recent climate trends have contributed to the establishment, growth, spread and survival of some alien species populations in some regions, but only *low confidence* that the species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated dispersal in mediating invasions.

Tree Mortality (see 4.3.3.1, Box 4-2) - Extensive tree mortality appears to be increasing globally, but there is *low confidence* in detection due to a lack of temporal and spatial coverage of tree mortality. In particular, the increase in reporting of mortality may reflect greater observation effort rather than a real increase in mortality. In many cases, tree mortality can clearly be linked directly to climate impacts, especially heat and drought. However, attribution to directional climate change over the last several decades is difficult (*low confidence*) due to lack of time series measurements for a large range of forested systems and the large number of confounding factors mediating tree mortality.

Boreal Forest Regime Shift (see 4.3.3.1.1, Box 4-4) - An increase in tree mortality is observed in many boreal forests, with particularly widespread dieback related to insect infestations in North America. Tree health in boreal

forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection of a clear temporal trend in morality at the global scale. Models and paleobotanical data indicate that regression of boreal forest at its southern edge is a predictable response to warming. High magnitudes of climate change over most of boreal forest also facilitate attribution to global warming. In some cases, tree mortality can be linked directly or indirectly (e.g., due to changes in insect and pathogen ranges) to fluctuations in climate. However, the lack of long-term data sets and high spatial heterogeneity means that attribution to climate change is of *low confidence*.

Amazon Forest Regime Shift (see 4.3.3.1.3, Box 4-3) - Long-term increases in tree turnover (increased mortality and growth) in the humid tropical forests of the Amazon basin have been documented with *moderate confidence*. In addition, two episodes of extreme drought over the last decade have led to increased mortality of large trees. There is *low confidence* that this represents a trend towards degradation of humid tropical forest, since structural changes in intact forests have been minor. Observed changes in tree turnover have been ascribed to a variety of mechanisms including rising CO_2 effects on vines, recovery from past disturbance and changing climate: the attribution to these various drivers is difficult due to limited temporal and spatial coverage. Models and experiments lend credence to a contribution of climate to increased tree mortality and growth. There is *very low confidence* in attribution of observations to climate change because of the short period of intensive monitoring records and because warming trends over the last several decades are weak in this region.

Tundra Regime Shift (see 4.3.3.4) - Field and satellite measurements indicate an increase in shrub growth and permafrost thawing in many areas of the Arctic tundra. Lack of temporal coverage makes it difficult to know if this is a strong directional signal leading to *medium confidence* in detection of a trend. It is not clear to what extent this presages boreal forest encroachment into tundra, which would have much larger impacts on ecosystem structure and function. Experiments, models and paleontological responses of tundra to past warming all indicate that the increase in shrub coverage and permafrost thawing are predictable responses to climate warming trends. High magnitudes of climate change over the last 50 years for most of the Arctic facilitate attribution. The lack of long-term monitoring data makes it difficult to attribute these changes to climate change with greater than *medium confidence*.

Cultural Landscapes (see 4.3.3.5) - There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes, that there is *very low confidence* that we can attribute these observations to climate change.

Evolutionary and Genetic Adaptation (see 4.4.1.2) - While there are an increasing number of observations of "rapid evolutionary" responses to climate variation, the number of species studied is extremely limited. In addition, it remains difficult to separate phenotypic from genotypic adaptation meaning that there is only *low confidence* that we are detecting a widespread signal of evolutionary or genetic adaptation to climate. An increasing number of models and experiments illustrate that "rapid evolutionary" responses are possible and even probable response to climate change. In a few cases, strong correlations between climate trends and changes in gene frequencies underlying phenological responses to climate trends suggest that climate change is an important driver of rapid evolution. The limited number of well-studied cases means there is only *low confidence* in attribution of adaptation as a generalized response to changes in climate over the last several decades.

4.3.2.1. Phenology

A large number of site-specific studies, and more recently satellite imagery, allow monitoring of phenology. The advance in spring events (e.g. breeding, bud burst, breaking hibernation, flowering, migrating,) has been reported for many regions, especially from the northern hemisphere but fewer in the southern hemisphere and for many plant and animal taxa. Since the AR4 many new studies showing phenological adaptations of species as response to climate change (e.g., amphibians: Kusano and Inoue, 2008; birds: Pulido, 2007; Thorup *et al.*, 2007; mammals: Adamik and Kral, 2008; Lane *et al.*, 2012; plants: Cleland *et al.*, 2007; Gordo and Sanz, 2009; plants and animal taxa: Høye *et al.*, 2007; Primack *et al.*, 2009) and meta analyses were published (observed data: Parmesan, 2006; Parmesan, 2007;

Thackeray *et al.*, 2010; Cook *et al.*, 2012; Ma and Zhou, 2012; Wolkovich *et al.*, 2012; experimental warming experiments: Musolin *et al.*, 2010; Cleland *et al.*, 2012).

Large-scale changes and variations in vegetation have been monitored by satellite since 1982 (White *et al.*, 2009). The Advanced Very High Resolution Radiometer (AVHRR) quantifies the differences in visible and near-infrared wavebands of outgoing radiation (NDVI) which is related to the quantity of photosynthetically-active vegetation. The times of maximum and minimum rate of change of NDVI provide a metric of the growing season. From 1982 to 2008 the NDVI-defined start of the growing season advanced by 5.4 days at the hemispheric scale, and the end was delayed by 6.6 days (Jeong *et al.*, 2011). Rates of change varied over time and at smaller scales. Changes were found to be strongly related to temperature trends, although changes in precipitation may also be key drivers, especially in more arid regions (McPherson, 2007). Studies with the more recent instrument, Moderate Resolution Imaging Spectrometer (MODIS), and other metrics such as Leaf Area Index (the ratio of leaf area to ground area; Ahl *et al.*, 2006) provide a similar picture at large scales, although results can differ at local scales due to the use of different instruments, indices and trend detection methods. The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period. Nevertheless, the general emerging picture of an advancement of the start of the growing season length is consistent with ground-based phenology studies. At a regional scale, a combination of species-level observations, meta-analysis, NDVI measurements and phenology modeling to reveal geographically different advancements in spring phenology of Chinese plant communities in different Ecoregions and Biomes between the 1960s and 2000s (Ma and Zhou, 2012).

Changes in breeding phenology are reported from various regions and different taxa (insects, birds, mammals, amphibians; e.g. Parmesan, 2006; Parmesan, 2007; Post *et al.*, 2008; Primack *et al.*, 2009). Various factors can be attributed to changes on breeding phenology, e.g. food availability, increasing spring temperatures. In the northern hemisphere several studies show advancements of egg laying dates in birds (e.g. Parmesan, 2007: -3.70 days/decade ± 0.7, n= 41 species in a meta-analysis). In mammals, Réale *et al.* (2003) found for the female North American squirrel (*Tamiascurus hudsonicus*) an advancement of 18 days of the mean parturition day in 10 years (1992-2002) in the Yukon area, Canada, coinciding with increasing abundance of white spruce cones, the major food source. For the southern hemisphere the opposite pattern, a significant delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 for two of nine seabirds in the Eastern Antarctic (Barbraud and Weimerskirch, 2006).

Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g. Sokolov, 2006; Adamik and Pietruszkova, 2008). Phenological response can differ with migration strategy in birds, such as short distant migrants show greater advancements in spring arrivals than long distant migrants (e.g. Saino *et al.*, 2009; but see Parmesan, 2006 for different patterns). Insects show also a variety of phenological responses to changing temperatures (e.g. reviewed in Robinet and Roques, 2010). Development rates speed up and for polyvoltine species an increase in number of generations attributed to increasing temperatures and a lengthening of the growing seasons due to earlier timing of last winter frost and later timing of first fall frosts) are reported (e.g. Menzel *et al.*, 2003; Kunkel *et al.*, 2004; Sunley *et al.*, 2006; Robinet and Roques, 2010)

A variety of environmental drivers could affect behavioral changes in species. Experimental-manipulation shows that higher temperatures lead to significantly earlier egg laying dates of the great tit (*Parus major*) in 5 out of 6 years (Visser *et al.*, 2009), but rates of seasonal warming may also be important (Schaper *et al.*, 2012). In a temperate region (Massachusetts, USA), declining sizes of migration cohorts or of populations appeared to account for a large amount of the variation in previously documented changes in migration times between 1970 and2002 (Miller-Rushing *et al.*, 2008). After accounting for changes in migration cohort size, migration distance, climatic variables, and migration date explained portions of the variation in migratory changes over time. Changes in migration phenology cannot only be attributed to changes in temperature changes but also to differing variability of changed feathers during moulting times, food availability at stop-over places and differing health conditions of individual species (Gordo, 2007).

Snow cover and snow depth can also be important factors. Interactions between temperature precipitation determining snowmelt changes, which is reported to lead to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye *et al.*, 2007) and earlier flowering in an alpine plant in the

Rocky Mountains, USA between 1975 and 2008 (Lambert *et al.*, 2010; Hülber *et al.*, 2010). Earlier snow melts are reported to decrease floral resources and can hence affect survival of dependent insects in mountain ranges in the USA across 1980, 1985, 1986 and 1989 (Boggs and Inouye, 2012). Mammals show also changes in phenology as effects of climate change induced changes on snowmelt pattern, especially hibernating species, ranging from advancements of emergence dates from hibernation (Ozgul *et al.*, 2010) due to earlier snowmelts or to delayed emergence dates (Lane *et al.*, 2012) due to delayed snowmelts. Delayed emergence from hibernation was also associated with decreased population growth rate (Lane *et al.*, 2012).

Experiments are an important source of information on physiological and phenological responses to changing climate, but some caution should be exercised when translating their results into future projections using models. Wolkovich *et al.* (2012), in a large meta-analysis, suggested that warming experiments substantially underpredict advances in the timing of flowering and leafing of plants. They also showed that experimentally-derived temperature sensitivities of species did not match the observations in the wild. However, in contrast, Gunderson *et al.* (2012) found good agreement between experimental warming and *in situ* observations. Experiments on wild species may also directly affect results; for example, flipper-tagging of penguins can alter their migratory behavior (Saraux *et al.*, 2011).

Generally, there is a great interspecific variability in phenological responses to changing climatic factors (e.g.: Gunderson *et al.*, 2012). Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. Parmesan (2007) found taxonomic groups to be advancing at significantly different rates, with amphibian breeding date advancing by eight times as much as other groups, birds and butterflies were not significantly different from each other, but both showed spring advancement three times stronger than for herbs and grasses. Since most butterfly species eat herbs and grasses as host plants, this suggests an increasing asynchrony between these two interacting groups. Thackeray *et al.* (2010) draw similar conclusions. Species unable to adjust their behavior, i.e. advancement of spring events to keep track with changing climates could be negatively affected. This may be particularly important in highly seasonal habitats (Both *et al.*, 2010). The degree, direction and strength of the asynchrony due to changing climatic variables depends on differences in the phenology of the interacting species (van Asch and Visser, 2007). Increasing temperatures may either bring species more into synch or more out of synch, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more towards a loss of synchrony (Visser and Both, 2005). Changes in (a)synchrony of interacting species is assumed to effect dynamical features of ecological communities such as trophic cascades, competitive hierarchies, and species coexistence (Nakazawa and Doi, 2012). Ahola *et al.* (2007) could show that the competition between the resident *P. major* and the migratory pied flycatcher (*Ficedula hypoleuca*) is increasing when the onset of breeding of both is becoming closer to each other and the abundances of both species are increasing (data: 1953–2005; South-Western Finland). This pattern resulted in a relative host change to more long-distant hosts. van Asch and Visser (2007) report increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) due to increasing spring temperatures and not changing winter temperatures (based on a descriptive model, oak data: 1975-1999, Netherlands, moth data: 1995-1999; Oosterhout, Warnsborn, Doorwerth, Arnhem; Netherlands). The edible dormouse (*Glis glis*), a nest predator advanced its hibernation termination significantly with -8 days per decade in the Czech Republic between 1975-2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four bird surveyed species (Adamik and Kral, 2008)

Cross taxa observations show high variation in species- and location specific responses to increasing temperatures in both direction and magnitude (e.g. Parmesan, 2007; Primack *et al.*, 2009; Thackeray *et al.*, 2010). Uncertainties and biases can be introduced in research that compares different taxonomic groups or geographic regions by often incomplete or non-overlapping time series, averaged geographical scales, lack of consideration of effects of local climatic variability (e.g. wind speed, climatic conditions at stop-over places) and mostly unknown pressures in winter ranges for migratory species (Hudson and Keatley, 2010). With too short time series long term trends in phenological changes cannot be detected, although responses to annual climate variability can often be characterized. However, some studies now extend over several decades (Cook *et al.*, 2008) or even 100 years (Naef-Daenzer *et al.*, 2012)**.** Given the geographical coverage and length over time over which studies are now available, there is high confidence (*robust* evidence, high agreement) that phenological shifts are occurring as a response to a warming climate.

4.3.2.2. Primary Productivity

Primary production is the process of plant growth that underpins energy flow through all ecosystems, enabling provisioning services such as crop, forest, livestock and fisheries harvest. It is also fundamental to the regulation of global carbon cycle (see 4.3.2.3. below). Trends in the amount, seasonal timing, variability, location and type of primary production are therefore important indicators of ecosystem function. Well-established theory, experimentation and observation all agree that primary production is directly and indirectly sensitive to almost all aspects of climate change as well as to many of the other changes simultaneously taking place in the world, such as the factors described in section 4.2.4. The complexity of the interactions between driving factors and the frequently non-linear form of the responses to them means that at a given location the net outcome can be an increase in productivity, no change or a decrease.

At continental-to-global scale two main sources of information on primary productivity are available. The first is precise and frequent measurements of atmospheric carbon dioxide, which once the known signal of fossil fuel emissions is removed, show clear patterns in space and time largely related to the primary productivity of the land and oceans. The relative contribution by the land, which consists of a sink term due to increased net productivity plus a source term due to land-use change, can be estimated using isotope measurements, emission databases and models (Canadell *et al.*, 2007). During the decade 2000 to 2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the postulated pre-industrial level, leading to a land sink of 2.6 $\pm$ 0.7 PgC/y (see WG1 chapter 6; Raupach *et al.*, 2008; Le Quere *et al.*, 2009). This net uptake of carbon by the land is highly variable year-to-year, in response to global climate models such as ENSO and major volcanic eruptions (Peylin *et al.*, 2005; Sitch *et al.*, 2008; Mercado *et al.*, 2009). It is currently not possible to state with any degree of confidence that the net uptake of carbon on land has either increased or decreased over the past two decades (Raupach *et al.*, 2008).

It is possible to estimate the net uptake on land at subglobal scales, using inversion modelling techniques and the growing network of precision atmospheric observations. There is broad agreement that the net land uptake in largely-untransformed terrestrial ecosystems is globally distributed, almost equally between forested and non-forested ecosystems, but is offset in the tropics by a large carbon emission flux resulting from land-use change, principally deforestation (Pan *et al.*, 2011).

Space-based remote sensing can in principle monitor trends in vegetation cover and leaf area, from which primary productivity can be inferred. A commonly-used metric is the Normalised Difference Vegetation Index (NDVI), for which over 30 years of observations are available, covering most of the global land surface. The observed trends are discussed under the various ecosystem-specific discussions below. In some cases the trends are sufficiently strong and consistent to support a confident statement about the underlying phenomenon, but in many cases they are not. This may mean that no change has occurred, but simply reflect inadequacies in the indicator, method of analysis and length of the record. The AR4 reported a trend of increasing seasonally-accumulated NDVI ("greening") at high northern latitudes (Fischlin *et al.*, 2007; based on Sitch *et al.*, 2007), but later observations show a lower rate and no geographical uniformity (Goetz *et al.*, 2007). More than 25% of North American forest areas, excluding areas recently disturbed by fire, showed a decline in greenness and no systematic change in growing season length, particularly after 2000. NDVI trend analysis studies in rangelands show varying patterns around the world, with substantial areas of disagreement between studies (Millennium Ecosystem Assessment, 2005b; Bai *et al.*, 2008; Beck *et al.*, 2011a; Fensholt *et al.*, 2012). There is agreement that the Sahel showed widespread NDVI increase between the mid 1980s and about 2000, along with an increase in rainfall, but no consensus on whether the detected signal represents increased productivity by grasses, trees or forbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Hickler *et al.*, 2005; Prince *et al.*, 2007; Hellden and Tottrup, 2008; Seaquist *et al.*, 2009). In the period 2000 to 2009 no NDVI trend was apparent in the Sahel (Samanta *et al.*, 2011).

Tree rings record changes in tree growth over approximately the past millennium. Ring width and the wood density within a ring indicate tree productivity during the period represented by the ring. Isotopes within the ring reveal

changes in the environment to which the tree was exposed. Variations in tree ring parameters arise from many factors, including temperature, moisture stress, CO_2 fertilization and ozone damage. The most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010) so tree ring-based conclusions for more recent dates are based on a smaller body of evidence. Sites which are not sensitive to environmental changes may therefore be under-represented. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in 4.3.2.3) are an alternate data source for recent decades. Tree ring studies may not be representative of forests in general, as most studies were specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010).

Many tree ring records show a tendency of accelerated tree growth during much of the 20th century (Briffa *et al.*, 2008), which often correlates with rising temperature. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s a number of tree ring records show a decline in tree growth (Wilson *et al.*, 2007). Several possible causes have been suggested for this, including increasing water stress and ozone damage.

4.3.2.3. Biomass and Carbon Stocks

Forests are routinely monitored for management and research purposes, typically by recording species composition and stem size distribution in hundreds of small plots. Forest carbon stock can be estimated from this and forest area data, usually derived from remote sensing. Repeated forest inventories in principle allow the growth rate and change in carbon stock to be estimated. Forest inventories were designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well-developed for northern hemisphere temperate and boreal forest (Nabuurs *et al.*, 2010; Ryan *et al.*, 2010; Wang *et al.*, 2010a). Data for tropical and southern hemisphere forests and woodlands also exist (Maniatis *et al.*, 2011; Tomppo *et al.*, 2010) but are typically less available and comprehensive (Romijn *et al.*, 2012). More and better data may become available due to advances in remote sensing (e.g. Baccini *et al.*, 2012) and the REDD+ initiative.

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais *et al.*, 2008; Luyssaert *et al.*, 2010) and the USA (Birdsey *et al.*, 2006). Canadian managed forests increased in biomass only slightly over 1990-2008, due to fires and beetle outbreaks (Stinson *et al.*, 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Malhi *et al.*, 2009a; Phillips *et al.*, 2009) forest biomass has generally increased in recent decades, dropping after a drought in 2005. Globally, mature forests are withdrawing from the atmosphere one fourth of human CO_2 emissions while regrowth forests withdraw an additional 17%. This global terrestrial sink is offset by the losses of forest carbon to the atmosphere through tropical deforestation and land-use (Pan *et al.*, 2011).

The carbon stock in global soils, including litter, peatlands and permafrost, is estimated to be in the order of 3300 PgC (Davidson *et al.*, 2011), which is about ten times more than is contained in forest biomass (Kindermann *et al.*, 2008). The size of this stock represents the balance of inputs from primary productivity and soil respiration. Soil respiration increases with increasing temperature, but the sensitivity remains uncertain (Davidson and Janssens, 2006). An analysis of long-term soil respiration measurements from around the world suggests that soil respiration has increased over the past two decades by an amount of 0.1PgC/y, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). Flooded coastal soils also show increases in respiration, larger than increases in production (Kirwan and Blum, 2011).

4.3.2.4. Evapotranspiration and its Role in the Terrestrial Water Cycle

Transpiration is affected by multiple factors (Luo *et al.*, 2008) including temperature, humidity, soil moisture, solar radiation and CO_2 concentration. Total evapotranspiration (ET: transpiration through plant stomata plus evaporation from the ground surface and leaf surfaces) is monitored with flux towers, but since most records are at most 15 years

duration (FLUXNET, 2012) there is insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations using the Penman-Monteith equation (Monteith, 1965; Penman, 1948) or simulated with models constrained by observations. Estimates of ET from 1120 globally distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.5 mm yr^{-2} (Wang *et al.*, 2010b), while other studies using constrained models in combination with other methods indicated trends of between 0.25 mm yr^{-2} to 1.1 mm yr^{-2} during the 1980s and 1990s but with a plateau or even decline since approximately 2000, attributed to reduced net radiation (Vinukollu *et al.*, 2011; Zeng *et al.*, 2012). A multi-model study using a data-driven empirical model and process-based land models (Jung *et al.*, 2010) also suggests that global evapotranspiration rose from the 1980s to the late 1990s but this trend then ceased, with increasing soil moisture limitations being cited as the cause.

Experimental studies demonstrate that increasing CO_2 concentrations leads to a decrease in transpiration and increase in intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance, Leakey *et al.*, 2009), which may act to offset climate-driven ET increases or precipitation decreases to some extent (Luo *et al.*, 2008). A two-year experimental study also showed that warming can also decrease grassland transpiration by leading to earlier spring senescence (Zavaleta *et al.*, 2003b). Historical changes in iWUE can be inferred from records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) and even the bodies of herbivores (Barbosa *et al.*, 2010) since iWUE has been shown to be related to the change in the carbon isotope discrimination $\Delta^{13}C$ (Duquesnay *et al.*, 1998). A meta-analysis of studies at 47 sites across 5 ecosystem types (Peñuelas *et al.*, 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since pre-industrial times (1850 or before) has also been found at several forest sites (Gagen *et al.*, 2011; Andreu-Hayles *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and also in a temperate semi-natural grassland since 1857 (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011).

4.3.2.5. Changes in Species Range, Abundance and Extinction

Species respond to climate change through genotypic and phenotypic adaptation, by moving out of unfavorable and into favorable climates, or by going locally or globally extinct (Dawson *et al.*, 2011, Bellard *et al.*, 2012; section 4.2.2). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied by large reductions in abundance (see section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for disease. Global extinctions result in the permanent loss of unique combinations of genes.

Substantial evidence has accumulated since the AR4 report reinforcing the conclusion that terrestrial plant and animal species' ranges have moved in response to warming over the last several decades and that this movement is projected to accelerate over the coming decades under high rates of climate change. Some changes in species abundances appear to be linked to climate change in a predictable manner with species abundances increasing in areas where climate has become more favorable and vice versa. In contrast, uncertainties concerning attribution of recent and projections of future global species extinctions due to climate change have become more apparent since the AR4 report.

Observed Species Range Shifts - The number of studies looking at observed range shifts and the breadth of species examined has greatly increased since the AR4 report. The most important advances since AR4 concern improvements in understanding the relationship between range shifts and changes in climate over the last several decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe, 2003; Parmesan, 2006; Fischlin *et al.*, 2007; Chen *et al.*, 2011) is an useful simplification of species response to changing climate. However, responses to warming are conditioned by changes in precipitation, land use, species interactions and many other factors. Investigations of the mechanisms underlying observed range shifts show that climate signals can often be detected, but the impacts of and interactions between changing temperature, precipitation and land use often result in range shifts that are downhill or away from the poles (Rowe *et al.*, 2010; Crimmins *et al.*, 2011; Hockey *et al.*, 2011; McCain and Colwell, 2011; Rubidge *et al.*, 2011; Pauli *et al.*, 2012;

Tingley *et al.*, 2012; Zhu *et al.*, 2012). There are large differences in the ability of species groups and species within species groups to track changes in climate through range shifts (Angert *et al.*, 2011; Mattila *et al.*, 2011; Chen *et al.*, 2011). For example, butterflies appear to be able track climate better than birds (community shifts - Devictor *et al.*, 2012; but see Chen *et al.* (2011 for range shifts) while some plants appear to be lagging far behind climate except in mountainous areas (Bertrand *et al.*, 2011; Doxford and Freckleton, 2012; Gottfried *et al.*, 2012; Zhu *et al.*, 2012). There is also growing evidence that responses at the "trailing edge" of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen *et al.*, 2011**;** Brommer *et al.*, 2012; Sunday *et al.*, 2012) and difficulties in detecting local extinction (Thomas *et al.*, 2006).

Rates of recent climate change have varied greatly across the globe ranging from rapid warming to cooling (Burrows *et al.*, 2011; Dobrowski *et al.*, 2013), so taking into account this spatial variation should enhance the ability to detect climate related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured in the regions where the range shifts were observed (Chen *et al.*, 2011), providing greater confidence in attributing range shifts than from range data alone. Average range shifts across taxa and regions in this study were 17 km poleward and 11 m up in altitude per decade, which are 2 to 3 times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin *et al.*, 2007). However, even this approach is an oversimplification since key climate drivers of species range modifications, e.g., temperature and precipitation, frequently have shifted in divergent geographical directions (Dobrowski *et al.*, 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley *et al.*, 2012). Overall, studies since the AR4 report show that species range changes are complex responses to interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope and breadth of species studied that provides *medium confidence* that species ranges have responded to recent changes in climate.

Future Range Shifts - Projections of future species range shifts since AR4 report have been dominated by studies using ecological niche models (ENMs) that estimate future ranges based on current relationships between climate and species distribution (also called “species distribution models”, or "bioclimatic models" when models depend entirely on climate factors; Peterson *et al.*, 2011). A variety of process-based species distribution models are also being developed and more widely used (Kearney *et al.*, 2009; Dawson *et al.*, 2011; Cheaib *et al.*, 2012). Recent model comparisons suggest that in some instances bioclimatic models predict larger range shifts than process-based models (Morin and Thuiller, 2009; Kearney *et al.*, 2010; Cheaib *et al.*, 2012) although in other cases process-based models predict larger shifts (Buckley *et al.*, 2012). Projected future species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see section 4.2.2 and above). There has been some progress in model validation, such as the use of hindcasting of observed recent or paleontological range shifts, but validation still needs to be reinforced using a wide array of data types (Green *et al.*, 2008; Pearman *et al.*, 2008; Nogues-Bravo *et al.*, 2010; Dawson *et al.*, 2011). A major limitation of these models is that the vast majority do not account for realistic species displacement rates (i.e., rates at which species are able to shift their ranges); as such, they only indicate changes in areas of favorable and unfavorable climate from which possible shifts in species distribution can be inferred.

A small, but growing number of new analyses and models developed since the A4 report permit the estimation the ability of a large range of species to track climate change. These projections are based on i) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie *et al.*, 2009; Burrows *et al.*, 2011; Chen *et al.*, 2011; Sandel *et al.*, 2011; Schippers *et al.*, 2011; Feeley and Rehm, 2012; Schloss *et al.*, 2012; Dobrowski *et al.*, 2013) and ii) species displacement rates across landscapes with and without habitat fragmentation for very broad range of species (e.g., Stevens *et al.*, 2010b; Nathan *et al.*, 2011; Barbet-Massin *et al.*, 2012; Kappes and Haase, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012; see additional references in Figure 4-6 legend). Figure 4-6 provides a simplified comparison of these rates as means of illustrating the projected abilities of species to track climate. This simplified analysis is coherent with more realistic projections of climate induced species displacement across landscapes, some of which include additional constraints such as

habitat fragmentation or competition (Barbet-Massin *et al.*, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012). Comparison of these rates indicates whether species are projected to be able to track climate as it changes, i.e., when species displacement capacity exceeds climate velocity. When displacement rates are lower than projected climate velocities this indicates that species may be unable to keep pace with climate change.

Rates of climate change over the 20th and projected for the 21st century are shown in Figure 4-6A. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections for a wide range of greenhouse gas emissions scenarios (i.e., IPCC RCP scenarios, Knutti and Sedlacek, 2012). Rates of global warming for land surfaces have averaged ca. 0.03 °C/yr since 1980. At the low end of projected future rates of warming, rates decrease over time reaching near zero by the end of the century (RCP 2.6). At the high end, projected rates increase over time and culminate above 0.06 °C/yr by the end of the century (RCP 8.5), and can exceed 0.08 °C/yr at the upper bound for this scenario. Background colors in Figure 4-6A indicate the degree to which species may be able or unable to track suitable climates based on corresponding climate velocities (Figure 4-6B) and rates of displacement for a broad range of species groups (Figure 4-6C). Blue background color indicates that nearly all species will be able to track climate change in all areas; orange indicates that some species will be unable to track climate especially in flat areas; and red indicates that many species groups will be unable to track climate except in mountainous regions.

Climate velocity depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-6B, Loarie *et al.*, 2009; Dobrowski *et al.*, 2013). For example, climate velocity is low in mountainous areas, because climatic gradients are strong, and in areas where climate change is low (Figure 4-6B, leftmost axis). Climate velocity is high (Figure 4-6B, rightmost axis) in flat areas (e.g., Amazon basin) or areas where projected climate change is high (e.g., Arctic regions). In flat areas, climate velocity may exceed 8 km/yr for the highest rates of projected climate change (SRES A2 or RCP 8.5).

Rates of displacement vary greatly within and among species groups (Figure 4-6C). Some species groups, notably plants and especially trees, have very low displacement capacity. Other species groups such as butterflies, birds and large vertebrates generally have a very high capacity to disperse across landscapes. Small-ranged species across several groups (amphibians, mammals and birds) are markedly absent from areas with high climate velocities in the past, suggesting a low dispersal capacity (Sandel *et al.*, 2011). Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of 10s to a few 100s of m/yr. Overall, many plant species are foreseen to be able to track climates only in areas of mountainous areas, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities (e.g., the Amazon basin), thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change. On a global average, many rodents, as well as some carnivores and freshwater mollusks are projected to be beyond their limits to track climate at high rates of climate change (i.e., >0.06°C/yr). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see above).

Humans can enhance species displacement by intentionally or unintentionally dispersing individuals or propagules (arrow on right of Figure 4-6C pointing upwards). For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner *et al.*, 2010). Human activities can also substantially reduce displacement rates. For example, habitat fragmentation typically reduces displacement rates, sometimes substantially (Eycott *et al.*, 2012; Hodgson *et al.*, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012; arrow on right pointing downwards). The degree to which habitat fragmentation slows displacement depends on many factors including the spatial pattern of fragmentation and corridors, maximum dispersal distances, population dynamics and the suitability of modified habitats as stepping-stones (Pearson and Dawson, 2003).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space and potentially experience large range contractions, whereas displacement that keeps pace with climate change may

allow some species to increase their range size (Menéndez *et al.*, 2008; Pateman *et al.*, 2012). Mountains will provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-6B, Colwell *et al.*, 2008; Engler *et al.*, 2011; Gottfried *et al.*, 2012; Pauli *et al.*, 2012; but see Dullinger *et al.*, 2012). An important exception is for species that are already at the tops of mountains (or near other boundaries) – they are among the most threatened by climate change because they cannot move upwards (Thuiller *et al.*, 2005; ; Raxworthy *et al.*, 2008; Engler *et al.*, 2011; Sauer *et al.*, 2011). The consequences of losing favorable climate space are not yet well understood. A variety of lines of evidence reviewed below indicate that in the absence of adaptation this leads to declining abundance and eventually local extinction in areas of unfavorable climate, with potentially large effects on biodiversity and ecosystem services (see Box 4-2). Adaptive responses of species are discussed in section 4.4.1.

Significant uncertainties arising from translating rates of warming into climate velocities and from estimating displacement rates mean that the ability to track future climate can only be projected with *low confidence* across all species examined. For trees there is *medium confidence* in these projections due to the large number of studies of past, current and future displacement rates (*robust evidence* and *medium agreement*). Climate velocities are calculated using a variety of methods and spatial resolutions making direct comparisons difficult, so climate velocities in Figure 4-6B are based on semi-quantitative comparisons of several studies (see Figure 4-6 legend) and have only *low confidence* (*limited evidence* and *medium agreement*). For the global average climate velocity (Figure 4-6B, center axis), lowest estimates are about one third of the values on the axis (e.g. Loarie *et al.*, 2009; 0.42 km/yr ≈ 0.03 °C/yr for projected SRES A1B 21st century global land warming). Highest estimates are about four times the values on the axis (Burrows *et al.*, 2011; 2.7 km/yr ≈ 0.02 °C/yr global land warming from 1960-2009), but these high estimates may be artifacts of very large spatial resolutions used in this analysis (Dobrowski *et al.*, 2013). In addition, the rates used in this analysis are based on temperature alone and most analyses suggest that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski *et al.*, 2013). Species displacement rates are calculated based on a very wide range of methods including rates of displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens *et al.*, 2010b). There are often large differences in estimates of dispersal rates across methods (e.g., Kinlan and Gaines, 2003; Stevens *et al.*, 2010b) due to intrinsic uncertainties in the methods and differences in the mechanisms included. For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins *et al.*, 2003; Meier *et al.*, 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated (e.g., mammals, birds and phytophagous insects). As such, the displacement rates for these species may be optimistic. For some species groups such as trees, there are a wide range of published estimates of displacement rates leading to *high confidence* in the estimates in Figure 4-6C. Considerably less is known about displacement rates for other species groups in response to climate change (e.g., some mammal groups, mollusks), so we have only *low* to *medium confidence* in estimates of their dispersal capacity.

[INSERT FIGURE 4-6 HERE

Figure 4-6: (A) Rate of climate change, (B) corresponding climate velocities and (C) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.03 °C/yr correspond to ca. 1.1 km/yr global average climate velocity. When compared to rates of displacement, this would exceed rates for most plants, many primates and some rodents. (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis, all other rates are calculated based on the average of the CMIP5 climate model ensembles for the historical period and for the future based on the four RCP emissions scenarios. The lower bound (17% of model projections are outside this bound) is given for the lowest emissions scenario and the upper bound for the highest emissions scenario. Data were smoothed using a 20-year sliding window, and rates are based means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century corresponding to each of the RCP scenarios are from Knutti and Sedlacek (2012). Colors in the background synthesize the ability of species to track climate through displacement. (B) Estimates of climate velocity were semi-quantitatively synthesized from seven studies using a diversity of analytical approaches and spatial resolutions (historical - Burrows *et al.*, 2011; Chen *et al.*, 2011; Dobrowski *et al.*, 2013; projected future - Loarie *et al.*, 2009;

Sandel *et al.*, 2011; Schippers *et al.*, 2011; Feeley and Rehm, 2012; Schloss *et al.*, 2012). The three axes represent estimated climate velocities are representative of mountainous areas (left), averaged across all global land area (center, usually geometric means), and regions that are flat or have high rates climate change (right). (C) Rates of displacement for terrestrial plants - predominantly based on dispersal and establishment - were derived from paleobotanical records, modern plant invasion rates and genetic analyses (Kinlan and Gaines, 2003). The box represents ~95% of the observations in Kinlan and Gaines (2003) and the bar represents a qualitative estimate of the median. Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark *et al.*, 2003; Kinlan and Gaines, 2003; McLachlan *et al.*, 2005; Nathan, 2006; Pearson, 2006) and modeled tree dispersal and establishment in response to future climate change (Higgins *et al.*, 2003; Iverson *et al.*, 2004; Epstein *et al.*, 2007; Goetz *et al.*, 2011; Nathan *et al.*, 2011; Meier *et al.*, 2012; Sato and Ise, 2012). The box represents ~95% of the estimates and the bar is a qualitative estimate of the median. Displacement rates for mammals were based on modeled dispersal rates of wide range of mammal species from Schloss *et al.* (2012). The box represents 1.5 x the inter-quartile range of the estimates in Schloss *et al.* (2012) and the bar is the median. Several groups of mammals have not been plotted because they include a relatively small number of species. Estimates for birds are based on observed rates of displacement (Chen *et al.*, 2011; La Sorte and Jetz, 2010) and on modeled dispersal rates in response to projected climate change (Schippers *et al.*, 2011; Barbet-Massin *et al.*, 2012), but very low confidence in these estimates makes it difficult to set bounds or indicate central tendency. Displacement rates for phytophagous insects are based on observed dispersal rates (Kinlan and Gaines, 2003; Stevens *et al.*, 2010b; Sekar, 2012). The qualitative estimate of median dispersal rate exceeds the highest rates on the axis and is on the order of 100 km/yr. These dispersal rates do not take into account limitations imposed by host plants and habitats. Displacement estimates for freshwater mollusks correspond to the range of dispersal given for passive plus active dispersal mechanisms for upstream movement in Kappes and Haase (2012).]

Observed Changes in Abundance and Local Extinctions - Observations of range shifts imply changes in abundance; i.e., colonization at the "leading edge" and local extinction at the "trailing edge" of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* is reviewed above, in the AR4 report and by Cahill *et al.* (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure, also have occurred within existing range limits in response to recent global warming (*high confidence*) (Thaxter *et al.*, 2010; Bertrand *et al.*, 2011;Naito and Cairns, 2011; Rubidge *et al.*, 2011; Devictor *et al.*, 2012; Tingley *et al.*, 2012; Cahill *et al.*, 2013; Ruiz-Labourdette *et al.*, 2013). More confident attribution to recent global warming is hindered by confounding factors such as disease, land use change and invasive species (Cahill *et al.*, 2013). A new tentative conclusion since the AR4 is that climate related local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*) (Cahill *et al.*, 2013). This gives weight to concerns that biological interactions, which are poorly understood and modeled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn *et al.*, 2009; Bellard *et al.*, 2012; Urban *et al.*, 2012; Hannah, 2012).

A few examples illustrate the types of changes in abundance and local extinctions that are being observed and the challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in species populations come from high latitude ecosystems where non-climate drivers are of lesser importance. For example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to warming (Epstein *et al.*, 2007; Goetz *et al.*, 2011; Myers-Smith *et al.*, 2011). In the Antarctic, two native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*) have become more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill *et al.*, 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of an Emperor penguin population that has been attributed to regional changes in climate (Trathan *et al.*, 2011). The attribution to regional climate change is well supported, but the link to global warming is tenuous (Barbraud *et al.*, 2011).

Mountains also provide good examples of climate signals in abundance and local extinction because of very strong climate gradients. The AR4 report already highlighted these responses and the case for changes in abundance, in particular plants, has become stronger since then. For example, Pauli *et al.* (2012) reported an increase in species richness from plant communities of mountain tops in the European boreal and temperate zones due to increasing

temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in Southern Europe. An increase in the population size of warm adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried *et al.*, 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric nitrogen deposition, and forest management practices (Gottfried *et al.*, 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see below).

Projected Changes in Abundance and Local Extinction - Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. Projected areas of local extinction from these types of models ranging from near 0% of the current range to more than 95% (Settele *et al.*, 2008; Bellard *et al.*, 2012), and projected local colonization rates are equally variable. There has been progress in coupling species distribution and species abundance models for a wide range of organisms (Keith *et al.*, 2008; Midgley *et al.*, 2010; Matthews *et al.*, 2011; Schippers *et al.*, 2011; Oliver *et al.*, 2012; Renwick *et al.*, 2012). These approaches have the substantial advantage of predicting extinction risk directly, rather than by inference from changes in climate suitability (Fordham *et al.*, 2012). The main conclusion from these studies is species response to climate change is determined by a combination of factors, including its environmental niche, demographics and life history traits, as well as interactions among these factors (Aiello-Lammens *et al.*, 2011; Conlisk *et al.*, 2012; Fordham *et al.*, 2012; Swab *et al.*, 2012).

Changes in abundances will also be accompanied by changes in genetic diversity. At an intraspecific level, future climate change projections are projected to induce severe losses of genetic diversity (Balint *et al.*, 2011). In addition, there is theoretical and observational evidence that range contractions will reduce genetic diversity (Pauls *et al.*, 2013), but that the loss of genetic diversity will depend on rates of migration and range contraction (Arenas *et al.*, 2012). Reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Although future projections of climate change impacts do not appear to result in the loss of more phylogenetic diversity than expected by chance, projected species losses are projected to lead to phylogenetic homogenization across European plant, bird and mammal communities (Thuiller *et al.*, 2011, but see Davies *et al.*, 2011). Climate change may also compound losses of genetic diversity that already occurring due other global changes such as the introduction of alien species or habitat fragmentation (Winter *et al.*, 2009; section 4.2.4.6).

Observed Global Extinctions - Global species extinctions, many of them caused by human activities, are now close to the upper limits of observed natural rates of extinction in the fossil record (Barnosky *et al.*, 2011). Most extinctions over the last several centuries can be attributed to habitat loss, overexploitation or invasive species (Millennium Ecosystem Assessment, 2005a; Hofmann and Todgham, 2010; Cahill *et al.*, 2013). Of the more than 800 global extinctions documented by the IUCN, only 20 have been tenuously linked to recent climate change (Cahill *et al.*, 2013). Mollusks, especially freshwater mollusks, have by far the highest rate of documented extinctions of all species groups (Barnosky *et al.*, 2011). Mollusk extinctions are primarily attributed to invasive species, habitat modification and pollution — changes in climate are rarely evoked as a driver (Lydeard *et al.*, 2004; Regnier *et al.*, 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill *et al.*, 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have even been tenuously attributed to changing climate (Burkhead, 2012; Cahill *et al.*, 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds *et al.*, 2006). There have been more than 160 probable extinctions of amphibians documented over the last two decades, many of them in Central America (Pounds *et al.*, 2006; Kiesecker, 2011). The most notable cases have been the golden toad and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction ascribed to global warming with "very high confidence" (Pounds *et al.*, 2006; Fischlin *et al.*, 2007). This case has raised a number of important issues about attribution since i) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor and ii) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi *et al.*, 2008; Lips *et al.*, 2008; Collins, 2010; Anchukaitis and Evans, 2010; Vredenburg *et al.*, 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global

change pressures that poses the greatest threat to species (Pereira *et al.*, 2010; Hof *et al.*, 2011; Brook *et al.*, 2008). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming due to the very low fraction of species for which global extinction has been ascribed to climate change and tenuous nature of most attributions.

Projected Future Species Extinctions - Projections of future extinctions due to climate change have received considerable attention since the AR4 report. The AR4 report stated with *medium confidence* "that approximately 20-30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above pre-industrial levels" (Fischlin *et al.*, 2007). All model-based analyses since the AR4 broadly confirm this concern, leading to *very high confidence* that climate change will contribute to increased extinction risk for terrestrial species over the coming century (Pereira *et al.*, 2010; Sinervo *et al.*, 2010; Pearson, 2011; Warren *et al.*, 2011; Hannah, 2012; Ihlow *et al.*, 2012; Bellard *et al.*, 2012; Sekercioglu *et al.*, 2012; Wearn *et al.*, 2012). More generally, there is broad agreement that climate change will result in shifts in species' ranges and abundances, and that in the context of habitat fragmentation and other global change pressures this will contribute substantially to increased extinction risk of terrestrial species over the coming century (Pereira *et al.*, 2010).

However, work since the AR4 also calls into question the ability of models to accurately quantify future extinction risk. Modeling studies have used a wide range of methods to estimate future extinction risk, generally inferring extinction risk indirectly from changes in availability of habitat and rarely taking into account demographic factors such as dispersal ability and generation time (Akcakaya *et al.*, 2006). All studies project increased extinction risk by the end of the 21st century due to climate change, but these estimates range from below 1% to above 50% of species in the groups that have been studied (Pereira *et al.*, 2010; Bellard *et al.*, 2012; Cameron, 2012). However, most models do not incorporate key processes that link climate change to population change. For example, models rarely account for genetic and phenotypic adaptive capacity, dispersal, the effects of habitat fragmentation and loss, and community interactions as well as, in plants, the effects of rising CO_2 concentrations. A general paucity of approaches to model validation, the large variation in the climate sensitivity of species groups and uncertainties about timescales involved in range reduction to extinction all lead to *very low confidence* that models currently predict extinction risk accurately (Kuussaari *et al.*, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; Pearson, 2011; McMahon *et al.*, 2011; Araujo and Peterson, 2012; Bellard *et al.*, 2012; Fordham *et al.*, 2012; Kramer *et al.*, 2012; Hannah, 2012; Zurell *et al.*, 2012; Halley *et al.*, 2013). In addition, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate - with a few notable exceptions such as large land animal extinctions during the Holocene - has also led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin *et al.*, 2007; Willis and Bhagwat, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; Hof *et al.*, 2011; Willis and MacDonald, 2011; Wake, 2012). On the other hand, processes not accounted for in most models, such changes in biotic interactions such as pollination or predator-prey networks or non-linear changes in ecosystems with widespread consequences for resident species, mean that future extinction risks may also have been substantially underestimated, at least for certain areas and species groups (Schweiger *et al.*, 2008; Bellard *et al.*, 2012; Urban *et al.*, 2008; Nakazawa and Doi, 2012; Hannah, 2012) or overestimated (Menéndez *et al.*, 2008; Pateman *et al.*, 2012). Finally, there is growing awareness that most modeling analyses have not accounted for climatic variation at fine spatial scales (microclimate) that may increase (Randin *et al.*, 2009; Gillingham *et al.*, 2012; Suggitt *et al.*, 2012; Dobrowski *et al.*, 2013; Franklin *et al.*, 2013) or decrease (Trivedi *et al.*, 2008; Engler *et al.*, 2011) the likelihood of persistence of small populations under future climate change.

4.3.3 Impacts on Major Systems

This section covers impacts of climate change on broad types of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those areas of high vulnerability due to high exposure to climate change or that may be pushed past thresholds or "tipping points" by climate change.

Figure 4-7 provides an overview of two perspectives on estimating ecosystem vulnerability to climate change at the global scale. Figures 4-7A and 4-7B show projected future climate change in relationship to current inter-annual variability (Diffenbaugh and Giorgi, 2012; see similar analyses by Beaumont *et al.*, 2011; Williams *et al.*, 2007b).

This analysis highlights those areas where interannual variability is low compared to projected changes in climate, i.e., where future climate is likely to be outside of temperature fluctuations already experienced by ecosystems (Beaumont *et al.*, 2011; Diffenbaugh and Giorgi, 2012). In this analysis, it is the species and ecosystems around the equator that are projected to be the most exposed to the largest climate changes. High latitude systems do not appear as exposed to climate change in this analysis because they already experience high interannual variability. A number of lines of evidence suggest that this index of climate change is an appropriate way to view species and ecosystem vulnerability. In particular, there is evidence that tropical species have evolved to have narrow thermal limits due to low inter and intra-annual climate variability, and are also already near their upper thermal limits (ectotherms - Deutsch *et al.*, 2008; Huey *et al.*, 2012; birds - Sekercioglu *et al.*, 2012; trees - Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems where intra- and inter-annual variability in climate is high (e.g., Arctic and boreal ecosystems). However, there a number of physiological, evolutionary and ecological arguments that species and ecosystem vulnerability to climate change is considerably more complex (Corlett, 2011; Laurance *et al.*, 2011; Gunderson and Leal, 2012; Walters *et al.*, 2012, Gonzalez *et al.*, 2010). Figure 4-7C compares future and contemporary climate focusing on the absolute differences between future and current climates. In this case, high northern latitude systems have the greatest exposure to rising temperature (often exceeding 6°C in the RCP 8.5 scenario, Figure 4-7C), which all else being equal would make them more vulnerable to climate change. Indeed, the greatest degree of recent climate warming has occurred at high Northern latitudes (Burrows *et al.*, 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modeled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez *et al.*, 2010). There has been a tendency to oppose these two points of view; i.e., tropics are most vulnerable due to limited capacity of species to adapt to moderate global warming vs. high northern latitude systems are the most vulnerable because temperature increases are projected to the greatest at these latitudes. There are, however, there are good indications that both types of systems are highly vulnerable, but for different reasons (Corlett, 2011). This analysis highlights some of the reasons why there is a particularly strong focus on climate change impacts on tropical and high latitude systems in the following sub-chapters.

[INSERT FIGURE 4-7 HERE
Figure 4-7: Two climate indexes related to the vulnerability of terrestrial biomes to future climate change based on the RPC 8.5 scenario and the CMIP5 climate model ensemble (from Diffenbaugh and Giorgi, 2012). Panels A and B show the evolution of June-August temperatures in two ca. 20 year time slices around 2055 and 2090 in comparison with the hottest year during the period 1980-2005. Climate change is projected to result in many areas of the tropics and sub-tropics exceeding the temperatures during the 1980-2005 period 100% of the time by 2055. High northern latitude systems exceed this limit less frequently especially in the 2055 time slice. Panel C shows the absolute temperature differences between the 1980-2005 reference period and the 2090 time slice. High northern latitudes are exposed to much greater temperature increases than other regions and this is representative of the regional patterns of climate change for all time slices and emissions scenarios.]

An issue that emerged in the AR4 report and has grown substantially in prominence since then is that of thresholds or 'tipping points' (Lenton *et al.*, 2008; Scheffer *et al.*, 2009; Leadley *et al.*, 2010). Tipping points occur when positive feedback processes dominate over negative feedback loops, and the system begins to change as a result of both its internal dynamics and the external forcings, leading to a change in state that is difficult or slow to reverse (Lenton *et al.*, 2008; Scheffer *et al.*, 2009; Leadley *et al.*, 2010). In the AR5, tipping points are considered "a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated" (Glossary). Many examples of such thresholds have now been identified (Scheffer, 2009). Most are at the local scale, but the potential existence of ecological thresholds at a sufficient scale to have regional or global consequences is high. Posited examples include a drought and temperature threshold in the Amazon beyond which forest dieback and fires could contribute to large C fluxes to the atmosphere, or thawing of Arctic permafrost leading to emissions of CH_4 and CO_2 in sufficient quantities to further warm the Earth and amplify the permafrost warming (Lenton *et al.*, 2008; Leadley *et al.*, 2010). Ecosystem water balance thresholds that are surpassed through changes in temperature and precipitation, both gradual and through extreme events, may be a widespread phenomenon across a range of biomes (Knapp *et al.*, 2008a). Large-scale tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (section 4.2.2) and the sub-sections below highlight reasons for concern that they could occur in the near future. A thorough analysis of all

the highlighted tipping points is not possible in this section, so we have highlighted some of the most important and well-studied tipping points. Others are discussed in Lenton *et al.* (2008) and Leadley *et al.* (2010).

4.3.3.1. Forests and Woodlands

Forests and woodlands, are the principal providers of timber and pulp, biofuel and an important and steady source of good-quality water worldwide. They also supply other services, including food and, cultural services such as recreation. Forests are the habitat of a large fraction of the earth's terrestrial biodiversity, especially in tropical regions (Gibson *et al.*, 2011). Climate change and forests interact strongly. Climate and atmospheric CO_2 concentrations are major drivers of forest productivity and forest dynamics. At the same time forests play an important role in controlling climate through the large amounts of carbon they can store or release, and through direct effects on the climate such as the absorption or reflection of solar radiation (albedo), cooling through evapotranspiration and the production of cloud-forming aerosols (Arneth *et al.*, 2010;Pan *et al.*, 2011; Pielke *et al.*, 2011).

Combinations of ground based observations, atmospheric carbon budgets and satellite measurements indicate that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 861±66 PgC and stored 4.0 ± 0.7 Pg C $year^{-1}$ globally between 2000 and 2007 (Pan *et al.*, 2011; WG1 Chapter 6; Canadell *et al.*, 2007; Le Quere *et al.*, 2009). The carbon stored in intact and regrowing forests was counterbalanced by a release due to land-use change of 2.8±0.4 Pg C $year^{-1}$ over this same period due to tropical deforestation, resulting in a net C balance for global forests of 1.2±0.8 Pg C $year^{-1}$.

The phrase ’biophysical effects’ is shorthand for the effect forests have on the climate other than through being sources and sinks of greenhouse gases. These effects are now well documented, significant and are increasingly included in models of global and regional climate change. Observations and models indicate that boreal and tropical forests have the largest influence on climate, but for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation); and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire *et al.*, 2011; Pielke *et al.*, 2011). Overall, this means that the biophysical effect of boreal forests is to warm the atmosphere and tropical forests to cool the atmosphere, compared to non-forest systems (Davin and de Noblet-Ducoudre, 2010). It has also been shown that forests influence regional precipitation through biophysical effects: deforestation in the tropics can alter regional precipitation (Butt *et al.*, 2011) and there is growing evidence of similar effects in temperate forests (Pielke *et al.*, 2011).

The future of the interaction between climate and forests is unclear. The carbon stored by intact and regrowing forests appears have stabilized compared to the 1990's, after having increased in the 1970's and 1980's (Canadell *et al.*, 2007; Pan *et al.*, 2011). The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and simulation of C sequestration by climate change, rising atmospheric CO_2 concentrations and N deposition (Pan *et al.*, 2011). Most models suggest that rising temperatures, drought and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch *et al.*, 2008; Bowman *et al.*, 2009). Fires play a dominant role in driving forest dynamics in many parts of the world and the susceptibility to fire is projected to increase little for the lowest emissions scenario (RCP 2.6), but substantially for the high emissions scenario (RCP 8.5, Figure 4-8). Climate change-mediated disease and insect outbreaks could precipitate this transition (Kurz *et al.*, 2008). The greatest risks for large feedbacks from forests to climate arise from widespread tree mortality and fire in tropical forests and low latitude areas of boreal forests, as well as northward expansion of boreal forests into arctic tundra (Lenton *et al.*, 2008; Kriegler *et al.*, 2009; Good *et al.*, 2011).

[INSERT FIGURE 4-8 HERE
Figure 4-8: Forest Fire Danger Index (FFDI) and its changes simulated with the HadGEM2-ES Earth System Model (Jones *et al.*, 2011). Left column: 30-year mean FFDI (MacArthur, 1973; Noble *et al.*, 1980) for 1980-2010 (top) and 2070-2100 under RCP2.6 (middle) and RCP8.5 (bottom). Right column: differences in 30-year mean FFDI relative to 1980-2010 for 2070-2100 under RCP2.6 (middle) and RCP8.5 (bottom). Maps show 30-year means of

FFDI values calculated using daily model data, following the methodology of (Golding and Betts, 2008). FFDI is not shown where the simulated vegetation cover is less than 10% for the respective time period (colored grey).]

Recent evidence suggests that the stimulatory effects of global warming and rising CO_2 concentrations on tree growth may have already peaked in many regions (Charru *et al.*, 2010; Silva *et al.*, 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting via heat stress, drought stress, pest outbreaks and a wide range of other indirect impact mechanisms (Allen *et al.*, 2010a; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions, and attribution to climate change is difficult due to the multiplicity of mechanisms mediating mortality (Allen *et al.*, 2010a).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Secretariat of the Convention on Biological Diversity, 2010). It is unclear if the global trend to reduced forest loss will continue - there are substantial pressures to deforest for the production of food and biofuels (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011). However, there are a number of signs that tropical deforestation could slow substantially over the next few decades, although this is thought to require continued and substantial technological, institutional and policy innovations (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011; Westley *et al.*, 2011).

_____ START BOX 4-2 HERE _____

Box 4-2. Tree Mortality and Climate Change

Extensive tree mortality and widespread forest die-off linked to drought and temperature stress have been documented recently on all vegetated continents (Allen *et al.*, 2010a; Figure 4-9). Plot level datasets with appropriate spatial and temporal spans to detect long-term tree mortality trends (>20 years) are currently lacking for many regions (Anderegg *et al.*, 2013a), leading to *low confidence* in the ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem *et al.*, 2009; Peng *et al.*, 2011). Increased levels of tree mortality following drought episodes have also been detected across widespread plot networks in multiple tropical forests (Kraft *et al.*, 2010; Phillips *et al.*, 2010) and Europe (Carnicer *et al.*, 2011). Episodes of widespread die-off (high mortality rates of dominant tree species at a landscape scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa *et al.*, 2008; Carnicer *et al.*, 2011; Anderegg *et al.*, 2013b). Some widespread die-off events have occurred concomitant with infestation outbreaks (Raffa *et al.*, 2008), where pest populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz *et al.*, 2010). While strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is *low confidence* that this attribution can be made at the global scale.

Widespread die-off has influenced the species composition, structure and age demographics, and successional trajectories in these forests, and in some cases led to decreased plant species diversity and increased risk of invasion (Kane *et al.*, 2011; Anderegg *et al.*, 2012). Widespread mortality also has multiple effects on biosphere-atmosphere interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest biophysical properties and biogeochemical cycles (Breshears *et al.*, 2005; Kurz *et al.*, 2008; Anderson *et al.*, 2011).

Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently highly uncertain (McDowell *et al.*, 2011). Most current global scale vegetation models have little-to-no mechanistic representation of tree mortality (Fisher *et al.*, 2010; McDowell *et al.*, 2011). Nonetheless, a global analysis of tree hydraulic safety margins found that more than 70% of surveyed tree species operate close to their limits of water stress tolerance (Choat *et al.*, 2012), indicating that vulnerability to drought and temperature stress will not be limited to arid and semi-arid forests. Furthermore, timescales of tree and plant community recovery following drought are largely unknown, but preliminary evidence from several systems indicates recovery times may be shorter than recent drought return intervals, leading to “compounding” effects of multiple droughts (Mueller *et al.*,

2005; Anderegg *et al.*, 2013b; Saatchi *et al.*, 2013). Projected increases in temperature are also expected to facilitate expansion of insect outbreaks poleward and up in altitude, which may also cause or contribute to widespread tree mortality (Bentz *et al.*, 2010).

[INSERT FIGURE 4-9 HERE
Figure 4-9: Locations of observed drought- and heat-induced tree mortality around the Earth since 1970, documented by peer-reviewed studies. Global forest cover (dark green) and other wooded regions (light green) (FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen et al. (2010). Localities and measurement networks not included in Allen *et al.* (2010a), which are largely post-2009 studies, have been added to this map (white dots are specific locations and regional measurement networks are indicated by ovals). New locality references by region: Africa – Mehl *et al.* (2010); Gonzalez *et al.* (2012); van der Linde *et al.* (2011); Asia – Dulamsuren *et al.* (2009); Kharuk *et al.* (2013); Liu *et al.* (in revision); Zhou *et al.* (2013); Australasia – Brouwers *et al.* (2012, 2013); Fensham *et al.* (2012); Matusick *et al.*, 2012, 2013); Europe – Innes (1992); Peterken and Mountford (1996); Linares *et al.* (2009); Galiano *et al.* (2010); Vennetier and Ripert (2010); Aakala *et al.* (2011); Carnicer *et al.* (2011); Sarris *et al.* (2011); Marini *et al.* (2012); Vilà-Cabrera *et al.* (2012);Cailleret *et al.* (2013); North America – Fahey (1998); Barbour *et al.* (2007); Klos *et al.* (2009); Ganey and Vojta (2011); Peng *et al.* (2011); DeRose and Long (2012); Fellows and Goulden (2012); Kaiser *et al.* (2012); Kukowski *et al.* (2012); Millar *et al.*, 2012); Williams *et al.* (2012); Worrall *et al.* (2013); Garrity *et al.* (in review);South America – Enquist and Enquist (2011); Lewis *et al.* (2011); Saatchi *et al.* (2013).]

_____ END BOX 4-2 HERE _____

4.3.3.1.1. Impacts of climate change on boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition towards more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf; Lloyd *et al.*, 2011; Pearson *et al.*, 2013). At the same time, projections of climate-driven changes in boreal forests over the next few centuries remain divergent on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, non-linear or abrupt decline in some regions of the circum-Northern Hemisphere (Bernhardt *et al.*, 2011; Mann *et al.*, 2012; Scheffer *et al.*, 2012). Recent change (Box 4-2) and dynamic vegetation modeling (e.g., Sitch *et al.*, 2008) provide *high confidence* that regions of the boreal forest could witness widespread forest dieback. These shifts put at risk the boreal carbon sink, estimated at 0.5 Pg $year^{-1}$ in 2000-2007 (Pan *et al.*, 2011; Mann *et al.*, 2012).

Whereas boreal forest productivity is widely expected, with *medium confidence*, to increase as a result of warming (Hari and Kulmata, 2008; Bronson *et al.*, 2009; Zhao and Running, 2010; Van Herk *et al.*, 2011), and early analyses of satellite observations confirmed this trend in the 1980s, more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (Goetz *et al.*, 2007; Parent and Verbyla, 2010; Beck *et al.*, 2011b; de Jong *et al.*, 2011). The reasons for these "browning" trends have been debated but they are not directly related to fire disturbance (because fires produce random rather than systematic trends in time series). The best evidence to date indicates that warming-induced drought, specifically the greater drying power of air (vapor pressure deficit), induces photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp *et al.*, 2007; Bonan, 2008; Van Herk *et al.*, 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber *et al.*, 2000; Hogg *et al.*, 2008; Beck *et al.*, 2011b; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng *et al.*, 2011; Ma *et al.*, 2012). Conversely, productivity has increased at the boreal-tundra ecotone where more mesic conditions support an expected warming-induced growth response (Rupp *et al.*, 2001; McGuire *et al.*, 2007; Goldblum and Rigg, 2010; Beck *et al.*, 2011b).

There is *high confidence* that warming and drying, coupled with productivity declines, insect disturbance and associated tree mortality, also favor greater fire disturbance. The boreal biome fire regime has intensified in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke *et al.*, 2010; Turetsky *et al.*, 2011; Mann *et al.*, 2012). The latter is particularly important because more severe burning consumes soil organic matter to greater depth often to mineral soil, providing conditions that favor recruitment of deciduous species that, in the North American boreal forest, replace what was previously evergreen conifer forest (Johnstone *et al.*, 2010; Bernhardt *et al.*, 2011). Fire mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes net ecosystem carbon balance (Bond-Lamberty *et al.*, 2007; Goetz *et al.*, 2007; Welp *et al.*, 2007; Euskirchen *et al.*, 2009) as well as albedo and energy balance (Randerson *et al.*, 2006; Jin *et al.*, 2012; O'Halloran *et al.*, 2012). The most comprehensive study to date (Randerson *et al.*, 2006) focused on a set of flux tower measurements across a composition gradient, but this study was necessarily limited to a few sites in central Alaska. The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modeling studies that are relatively poorly constrained due to sparse *in situ* observations.

There is *high confidence* that the vulnerability of the boreal biome to this cascading series of interacting processes (Wolken *et al.*, 2011), and their ultimate influence on climate feedbacks, differs between North America and northern Eurasia. The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia – a region more than twice the size of the North American boreal biome, most of it underlain by permafrost conditions of the Siberian environment. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa *et al.*, 2010; Alexander *et al.*, 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in North America (Soja *et al.*, 2007; Mann *et al.*, 2012; Ali *et al.*, 2012; Marlon *et al.*, 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region.

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift, and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries will exacerbate additional warming (Schuur *et al.*, 2008; 2009; Tarnocai *et al.*, 2009; Romanovsky *et al.*, 2010; Schaefer *et al.*, 2011; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition and biology (e.g., Mackelprang *et al.*, 2011). The degree of thermokarsting associated with different substrates, and associated topographic relief, is tremendously variable because boreal vegetation in latter successional stages (evergreen conifers in North America) insulate permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and other factors such as fire disturbance interactions with both vegetation cover and soil organic depth as insulating layers (Jorgenson *et al.*, 2010; Grosse *et al.*, 2011). This variability, and vulnerability, is poorly represented in earth system models (McGuire *et al.*, 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example by removing forest cover to expose the land surface to winter temperatures (Zimov *et al.*, 2009) are impractical not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Impacts of climate change on temperate forests

The largest areas of temperate forest are found in eastern North America, Europe and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing growing season length, rising atmospheric CO_2 concentrations, nitrogen deposition and forest management – specifically regrowth following formerly more intensive harvesting regimes (Ciais *et al.*, 2008). The relative contribution of these factors has been the subject of

substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic. With the exception of Europe (Ciais *et al.*, 2008), the relative contribution of anthropogenic and environmental factors to forest growth and carbon uptake rates remains to be quantified.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence; high agreement),* absorbing 0.7±0.08 Pg C $year^{-1}$ from 1990 to 1999 and 0.8±0.09 from 2000 to 2007 (Pan *et al.*, 2011).This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including: a reversal of tree growth enhancement in some regions (N America - Silva *et al.*, 2010; Silva and Anand, 2013; Europe - Charru *et al.*, 2010; Bontemps *et al.*, 2011; Kint *et al.*, 2012); increasing tree mortality (Allen *et al.*, 2010a, Box 4-2); and changes in fire regimes, insect outbreaks and pathogen attacks (Adams *et al.*, 2012; Edburg *et al.*, 2012). In north-eastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica L.*) have been attributed to decreasing water availability (Charru *et al.*, 2010). These trends threaten the substantial role of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the late 20th century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or heatwaves (Charru *et al.*, 2010; Silva *et al.*, 2010). Extreme climate events have had a major impact on temperate forests over the last decade (Witte *et al.*, 2011; Kasson and Livingston, 2012; Ciais *et al.*, 2005). Extensive forest fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte *et al.*, 2011). The complex interactions between climate and forest management in determining susceptibility to extreme events make it difficult to unequivocally attribute these events to recent climate warming (Allen *et al.*, 2010a). There is *low confidence (limited evidence; medium agreement)* that climate change is threatening the temperate forest carbon sink directly or indirectly.

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of DGVM models showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially as a result of potential gains in tree cover in eastern North America and Europe; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch *et al.*, 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (He *et al.*, 2007; Sitch *et al.*, 2008; Ni, 2011; Peng *et al.*, 2009). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change are characterized by tipping points. The feedback mechanisms operating in boreal and tropical forests which lead to tipping point behavior appear to be less dominant in temperate forests (Bonan, 2008). There is *low confidence (medium evidence; low agreement)* on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and up in altitude in response to climate change (Dale *et al.*, 2010; Ogawa-Onishi *et al.*, 2010; Hickler *et al.*, 2012). Associated long-term projected range shifts generally vary from several km to several tens of km per decade, most probably cannot achieve such high rates by natural migration (*e.g.* Chmura *et al.*, 2011, see also 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g. Dale *et al.*, 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Kearney *et al.*, 2010; Kramer *et al.*, 2010; Morin and Thuiller, 2009; Cheaib *et al.*, 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the next century in China (Ni, 2011). New approaches to modelling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin *et al.*, 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman *et*

al., 2008, Allen *et al.*, 2010b, Garreta *et al.*, 2010). Model projections are qualitatively coherent with observations that temperate forest species are already moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir *et al.*, 2008). There is *medium confidence (medium evidence; medium agreement)* that temperate tree and animal species are migrating poleward and upward altitudinally.

4.3.3.1.3. Impacts of climate change on tropical wet and dry forests

The responses of tropical forests to variability and change in climate and atmospheric CO_2 concentration are superimposed upon the direct influences of human activities. Humans modify the composition and structure of tropical forests through the harvest of individual plants or animals and through management interventions to favor some species or structural features over others. Humans also convert forests to cropland or grazing land and influence forest exposure to ignition sources. Forest conversion is the best understood change that is underway in tropical forests. Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes.

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO_2 effects on photosynthesis and transpiration (see section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO_2 concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008) although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass, (Körner and Basler, 2010). DGVMs and the current generation of Earth System Models, including those used within CMIP5 (e.g., Jones *et al.*, 2011) generally use formulations for CO_2 effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar *et al.*, 1980; Ball *et al.*, 1987;Stewart, 1988; Collatz *et al.*, 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox *et al.*, 1998) that pre-dates larger ecosystem-scale studies, although some models have been optimized on the basis of more recent data (Jones *et al.*, 2011).

A second important source of uncertainty is the rate of future CO_2 and temperature rise (Betts *et al.*, 2012). Modelled simulations of future climate in tropical forest regions indicate with *high confidence (robust evidence, high agreement*) that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between climate models (WG1 Annex A), although there is *medium confidence* (*medium evidence, medium agreement*) that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation (Malhi *et al.*, 2009b). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO_2, and varies depending on the climate and vegetation model that is used (Scholze *et al.*, 2006; Zelazowski *et al.*, 2011) (Sitch *et al.*, 2008) Recent model medley studies (Cox *et al.*, 2013; Huntingford *et al.*, 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is *less likely* to undergo major retractions or expansions by 2100 through climate change alone as previously predicted (Cox *et al.*, 2000).

Changes in the species composition and biomass of moist tropical forests observed in networks of long-term forest plots in moist tropical forests are generally consistent with increasing WUE associated with the rising concentration of CO_2. Lianas and fast-growing tree species are increasing, as is forest biomass (Phillips *et al.*, 2002; Phillips *et al.*, 2005; Lewis *et al.*, 2009a; Lewis *et al.*, 2009b; Lewis *et al.*, 2011). Faster tree growth could also result from changes in solar radiation and the ratio of diffuse to direct radiation (Mercado *et al.*, 2009; Lewis *et al.*, 2009a; Brando *et al.*, 2010). There is *low confidence* (*limited evidence, medium agreement*) that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO_2. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood *et al.*, 2012), but is not yet observed as changes in forest biomass (except Clark *et al.*, 2003).

Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in moist tropical forests (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture depletion in two rainfall exclusion experiments (Nepstad *et al.*, 2007; Fisher *et al.*, 2008) and above a critical level of weather-related fire intensity in a prescribed burn experiment (Brando *et al.*, 2012). These experimental results were corroborated by observations of increased tree mortality during the extremely severe 2005 drought in the Amazon (Phillips *et al.*, 2009) and extensive forest fire (Alencar *et al.*, 2006; Aragão *et al.*, 2008; Alencar *et al.*, 2011; Box 4-3). There is *medium confidence* (*medium evidence, high agreement*) that moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods. There is *low confidence* (*limited evidence, low agreement*) that the severe droughts that have affected the Amazon region are associated with climate change (Shiogama *et al.*, 2011).

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels Cochrane, 2003. Selective logging, drought, and fire itself can reduce this fire resistance by killing trees, thinning the canopy and allowing greater heating of the forest interior; Uhl and Kauffman, 1990; Ray *et al.*, 2005; Curran *et al.*, 2004; Box 4-3). Land use often increases the ignition sources in tropical landscapes (Silvestrini *et al.*, 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence* (*robust evidence, high agreement*) that forest fire frequency and severity is increasing through the interaction between severe droughts and land use.

There are an estimated one million square kilometres of dry tropical forests in the world (Miles *et al.*, 2006), defined as forests occurring in tropical regions characterized by pronounced seasonality in rainfall distribution (Mooney *et al.*, 1995). More than half of the remaining tropical dry forests (54%) are located in South America. Approximately one third of the remaining tropical forests in the Americas are predicted to experience "severe climate change" by 2055, defined as an increase in air temperate of at least 2.5 deg. C and/or a decrease in precipitation of at least 50 mm a^{-1}. Less than one fifth of forests in other tropical dry forest formations are faced with this level of climate risk (Miles *et al.*, 2006). Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk (Miles *et al.*, 2006).

_____ START BOX 4-3 HERE _____

Box 4-3. A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-induced, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon "forest dieback") has improved. Modeling studies indicate that the likelihood of a purely climate-driven dieback in 2100 is lower than previously thought (Malhi *et al.*, 2009b; Good *et al.*, 2013; Cox *et al.*, 2013; Huntingford *et al.*, 2013) and there is now *medium confidence* (*robust evidence, medium agreement*) that climate change alone will not lead to widespread forest loss during this century. Meteorological fire danger is projected to increase (Golding and Betts, 2008; Betts *et al.*, submitted; Figure 4-8). Field studies and regional observations, have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land-use activities that could drive a fire-mediated, self-reinforcing dieback in this century. There is now *medium confidence* (*medium evidence, medium agreement*) that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured pyrophilic woody vegetation.

Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during annual dry seasons (Uhl and Kauffman, 1990; Ray *et al.*, 2005). Forest susceptibility to fire increases through canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and Kauffman, 1990; Ray *et al.*, 2005; Barlow and Peres, 2008), previous forest fire (Balch *et al.*, 2008; Brando *et al.*, 2012), severe drought (Alencar *et al.*, 2006), or drought-induced tree mortality (Nepstad *et al.*, 2007; da Costa *et al.*, 2010). The impact of fire on tree mortality is also weather-dependent. Under very dry, hot conditions, fire-related tree mortality can increase sharply (Brando *et al.*, 2012). Under some circumstances, tree damage is sufficient to allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to

further burning (Veldman and Putz, 2011). There is *high confidence* (*robust evidence, high agreement*) that logging, severe drought, and previous fire increase Amazon forest susceptibility to burning.

Landscape level processes further increase the likelihood of forest fire. Ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini *et al.*, 2011) (*high confidence*: *robust evidence, high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa *et al.*, 2007; Butt *et al.*, 2011; Knox *et al.*, 2011) (*low confidence*: *medium evidence, low agreement*) or through smoke, that can inhibit rainfall under some circumstances (Andreae *et al.*, 2004) (*low confidence*: *medium evidence, low agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Shiogama *et al.*, 2011).

In sum, fire-mediated changes in Amazon forests are self-reinforcing through increases in tree mortality, forest susceptibility to fire, ignition sources, and regional rainfall inhibition (Figure 4-10). If current patterns of deforestation, logging, severe drought, and forest fire continue into the future, 55% of the region's forests will be cleared or degraded by 2030, even without invoking positive feedbacks with regional climate, releasing 20±10 Pg of carbon to the atmosphere (Nepstad *et al.*, 2008) (*low confidence*: *low evidence, medium agreement*). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo *et al.*, 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished (Soares-Filho *et al.*, 2012), if deforestation declines, or if cleared lands are reforested (Nepstad *et al.*, 2008). The 76% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2012) demonstrates that large-scale mitigation of a fire-mediated tipping point could be feasible.

[INSERT FIGURE 4-10 HERE
Figure 4-10: The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire increases the likelihood of subsequent burning, especially if burning is followed by forest invasion by grasses or flammable herbs. Deforestation inhibits rainfall in the region and provides ignition sources to flammable forests, contributing to this dieback.]

_____ END BOX 4-3 HERE _____

4.3.3.2. Rangelands and Drylands, including Mediterranean-type Systems

The following sections treat a wide range of terrestrial ecosystems covering a large part of the terrestrial surface, whose unifying features are that they are not classified as forests and they typically exhibit strong water stress for several months each year. Grasses, grass-like plants and herbs are usually a major part of their vegetation cover. The principle land use often involves either wild or domestic herbivores.

4.3.3.2.1. Savannas

Savannas are defined as mixtures of coexisting trees and grasses. The geographical distribution of tropical savannas is determined by temperature, the seasonal availability of water, fire and soil conditions (Ellery *et al.*, 1991; Walker and Langridge, 1997; Staver *et al.*, 2011) and is therefore inferred to be susceptible to climate change. The proportion of trees and grasses in savannas is considered inherently unstable under some conditions (DeMichele *et al.*, 2011; Staver *et al.*, 2011; Wake, 2012). Savannas are characterized by annual to decadal fires of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major global source of pyrogenic emissions from land to atmosphere (Schultz *et al.*, 2008; van der Werf *et al.*, 2010). The differential effects of climate change, rising CO_2, fire and herbivory on trees and grasses have the potential to alter the structure, composition and ecosystem service delivery capacity of mixed tree-grass systems (e.g. Hughes *et al.*, 2006). Since tropical savannas occupy about an eighth of the global land surface, and

mixed tree-grass systems outside the tropics cover a similar area, small changes in their structure or fire regime can have globally-significant effects on the emission or uptake of radiatively-active gases and particles.

There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so (*high agreement, robust evidence*: Cabral *et al.*, 2009; Angassa and Oba, 2008; Moleele *et al.*, 2002; Wigley *et al.*, 2009; Witt *et al.*, 2009; Lunt *et al.*, 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area as tree biomass and soil organic matter (Hughes *et al.*, 2006; Liao *et al.*, 2006; Knapp *et al.*, 2007; Throop and Archer, 2008; Boutton *et al.*, 2009), changes in hydrology (Muñoz-Robles et al 2011) and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert *et al.*, 2008; Van Auken, 2009), rising CO_2 (Bond and Midgley, 2012; Buitenwerf *et al.*, 2012), climate variability and change (Eamus and Palmer, 2008; Fensham *et al.*, 2009) or two or more of these factors acting in combination (Ward, 2005; Bond *et al.*, 2008). As yet there are no studies that definitively attribute the relative importance of the various causes of woody plant biomass increase in savannas and grasslands, but there is *medium agreement* and *robust evidence* that climate and atmospheric changes are contributing factors in many cases. The increased growth rate of C3 trees relative to C4 grasses under by rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO_2 experiments with savanna saplings (Kgope *et al.*, 2010). A vegetation model of grasslands, savannas and forests suggests that rising CO_2 does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO_2 concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO_2 exposure but different land use histories, topographic position or soil depth (Wu and Archer, 2005; Wiegand *et al.*, 2005) imply that land management, water balance and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran *et al.*, 2005), suggesting that increases in rainfall could lead to increased tree biomass. In some places the savanna boundary is moving into former grasslands on elevation or climate gradients (Breshears, 2006).

It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to more savanna-like conditions in parts of the Amazon basin (Malhi *et al.*, 2009a; Box 4-3). In parts of Central Africa, forests have been observed to be moving into adjacent savannas and grasslands (Mitchard *et al.*, 2009), possibly due to depopulation and fire changes. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Tng *et al.*, 2012; Bowman *et al.*, 2011

4.3.3.2.2. Grasslands and shrublands

Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (e.g., Sala *et al.*, 1988; Snyman and Fouché, 1993; Fay *et al.*, 2003; Peñuelas *et al.*, 2004, 2007; Prieto *et al.*, 2009; Wu and Chen, 2013) Other factors being equal, grasslands and shrublands are in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production. Grasslands are exposed to rising CO_2, which is postulated to stimulate plant production, but more so for temperate grasses, herbs and woody plants with a C3 photosynthetic system than for C4 tropical grasses (see section 4.2.4.4). Some grasslands are simultaneously exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point and decreases it thereafter (see section 4.2.4.2, Bobbink *et al.*, 2010; Cleland and Harpole, 2010). Most rangelands are subject to grazing and fire. All these factors may have interactive effects, and species composition changes may overwhelm or alter the physiological climate effects (Suttle *et al.*, 2007).

Drawing on published studies, Ravi *et al.* (2010) found that changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world. They predict increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation); in particular highlight changes in hydrology and the erosion of soil by wind.

Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon assimilation (e.g. Peñuelas *et al.*, 2004, 2007; Beier *et al.*, 2008; Sowerby *et al.*, 2008; Albert *et al.*, 2011; Albert *et al.*, 2012; Miranda *et al.*, 2009; Selsted *et al.*, 2012; Walter *et al.*, 2012). In a controlled experiment with communities of tallgrass prairie species in Kansas, Fay *et al.* (2008) showed that changes in the interval between rainfall events and the rainfall delivered by individual storms altered carbon assimilation and respiration rates independently of changes in the total amount of water supplied. A similar experiment on a Mediterranean semiarid grassland community (Miranda *et al.*, 2009) found that delayed watering led to decreases in plant productivity and to delayed flowering. Species diversity was not affected by delayed onset of rain; however, it was reduced by changes in the frequency, amount and seasonality of wetting. In the Mongolian steppe (Shinoda *et al.*, 2010), drought reduced the above ground plant mass but did not substantially affect the root mass. A subset of species did not recover to pre-drought levels once precipitation returned to normal levels. A water and temperature manipulation experiment in China indicated that changes in water balance had a stronger effect on grassland microbial processes leading to carbon storage than changes in temperature (Liu *et al.*, 2009). Engler *et al.* (2011) emphasized that precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompanies warming. Vohland and Barry (2009) reviewed the effectiveness of in situ rainwater harvesting (RWH) as an adaptation to climate change in sub-Saharan Africa and concluded that it conferred higher food security and income, but may strengthen conflicts between nomadic and sedentary populations.

Experimental manipulation of six European shrublands on a latitudinal gradient showed the response to warming and drought to depend on site, year and plant species (Peñuelas *et al.*, 2004, 2007). Droughts decreased aboveground net primary production two thirds of the sites. Responses to warming were weaker in the presence of aridity. Gao and Giorgi (2008) identified the southern Mediterranean as particularly vulnerable to water stress and desertification processes under climate change conditions. Analyzing 168 site-years of eddy covariance measurements, Wu and Chen (2013) found summer drought to reduce both summer gross primary production and net ecosystem production in grasslands and crops of North America.

A European gradient study (Emmett *et al.*, 2004), showed that N mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions. An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby *et al.*, 2008, 2010). Responses of shrublands to drought may partly be driven by changes in the soil microbial community (Jensen *et al.*, 2003) or changes in soil fauna (Maraldo *et al.*, 2008).

Beier *et al.* (2008) found that nitrogen limitation reduces acclimation in plant production, as a result of an asymmetrical response to warming between the carbon and nitrogen cycles. Decreased tissue concentrations of phosphorus was also associated with warming and drought (Peñuelas *et al.*, 2004; Beier *et al.*, 2008; Peñuelas *et al.*, 2012). strong interactions of warming with disturbances have been observed leading to increased nitrogen leaching from shrubland ecosystems (Beier *et al.*, 2004).

N fertilization and nighttime warming caused soil and plant community responses within one season in a Chihuahuan semi-arid desert (Collins *et al.*, 2010). In contrast, Grime *et al.* (2008) found little species composition change after 13 years of manipulation of water and temperature in an infertile grassland in England. The community composition of subalpine grasslands in Switzerland have changed relatively little over the past fifty years (Vittoz *et al.*, 2009). The changes that did occur were largely associated with changes in land management rather than climate, although they were consistent with warming trends.

Sommer *et al.* (2010) used global empirical relationships between plant species richness and climate variables such as temperature, moisture and radiation to project richness changes under future climates. This method is independent of the usual species-by-species or biome-based climate niche approach, but its predictions apply to the long-term equilibrium outcome, rather than changes in the next few decades. In most temperate and arctic regions, the capacity

to support richer (i.e. more diverse) communities increases with rising temperature, while the projections indicate a strong decline in capacity to support species-rich communities in most tropical and subtropical regions.

Many grasslands, shrublands and savannas are characterized by relatively frequent but low-intensity fires. The fire frequency, intensity and seasonality in southern Africa are primarily under climate control, and secondarily influenced by management (Archibald *et al.*, 2009). In South America, El Niño-Southern Oscillation climate modes strongly influence on area burned in Colombian grasslands (Armenteras-Pascual *et al.*, 2011). Fire frequency in grasslands and forests in Australia is projected to increase, due to climate change (Pitman *et al.*, 2007). Since it is well-established that plant species composition is sensitive to the fire regime (e.g. Gibson and Hulbert, 1987; Uys *et al.*, 2004; Gill *et al.*, 1999 and many other studies) this provides an indirect mechanism by which climate change can lead to species composition change in grasslands and rangelands.

Relatively little is known regarding the combined effect of climate change, other global change factors and increasing use pressure by large mammal herbivores in rangelands, nor on the consequences for pastoral livelihoods that depend on rangelands (Thornton *et al.*, 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35 % of the global land surface. Deserts are sparsely populated, but the people who do live there are amongst the poorest in the world (Millennium Ecosystem Assessment, 2005b). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley circulation. The descending air on the poleward side of the Hadley circulation results in decreased rainfall (Mitas and Clement, 2005; Seidel *et al.*, 2008; Johanson and Fu, 2009; Lu *et al.*, 2009; Zhou *et al.*, 2011) and which determines the location of the broad band of warm deserts lands approximately 15-30° N and S of the equator. Recent satellite data show a greening trend in the Sahel, associated with a return to wetter climates following a multidecade dry spell. There may be a feedback to the global climate from an increase in desert extent (Alkama *et al.*, 2012), which differs in sign between deserts closer to the equator than 20° and those closer to the poles. In model simulations, extension of the 'warm deserts' causes warming, while extension of the 'cold deserts' causes cooling, in both cases largely through albedo-mediated effects. Two special circumstances of desert areas are important with respect to climate change. Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola *et al.*, 2009). Most deserts are already extremely hot, and therefore further warming will probably be physiologically injurious rather than beneficial. Secondly, the ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006), often involving the concatenation of a number of quasi-independent events. According to a conceptual model elaborated by Lapola *et al.* (2009) some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change.

Deserts are expected to become warmer and drier at a faster rate than other terrestrial regions (Stahlschmidt *et al.*, 2011). The warm deserts are already extremely hot, and therefore further warming is generally physiologically injurious rather than beneficial. Ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006), often involving the concatenation of a number of quasi-independent events. According to a conceptual model elaborated by Stahlschmidt *et al.* (2011) some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change.

4.3.3.3. Rivers, Lakes, Wetlands and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon *et al.*, 2006; Vörösmarty *et al.*, 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001, Bunn and Arthington, 2002; Nilsson *et al.*, 2005). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally extinct from their rivers (Tockner *et al.*, 2008). Pollution from cities and agriculture, especially nutrient

loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, freshwater systems have the highest rates of extinction of any ecosystem (as much as 4% pa for some groups - e.g. crayfish, mussels, fishes and amphibians in North America), with estimates that at least 10,000-20,000 freshwater species are extinct or at risk (Strayer and Dudgeon, 2010). This is particularly significant considering that freshwater habitats support 6% of all described species, including approximately 40% of fish diversity and a third of the vertebrate diversity (Dudgeon *et al.*, 2006; Balian *et al.*, 2008).

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO_2), or one third of the world's soil carbon stock (Limpens *et al.*, 2008; Page *et al.*, 2011). About 14-20% of the world's peatlands are currently used for agriculture (Oleszczuk *et al.*, 2008) and many, particularly peat swamp forests in Southeast Asia, are still undergoing major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens *et al.*, 2008; Hooijer *et al.*, 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release 1,400 Mg CO_2 ha^{-1} (Murdiyarso *et al.*, 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page *et al.*, 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frolking *et al.*, 2011) with large inter-annual variability.

It is *very likely* that these stressors to freshwater ecosystems and peatlands will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and intensification of agriculture (Vörösmarty *et al.*, 2000; Malmqvist *et al.*, 2007; Dise, 2009). However, climate change will have significant additional impacts on freshwater ecosystems (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including arctic and subarctic bog communities on permafrost, and alpine and arctic streams and lakes (see 4.3.4.4; Smith *et al.*, 2005; Smol and Douglas, 2007a). It is noteworthy that these high latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty *et al.*, 2010). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also *likely* to be further impacted by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

Evidence of rising stream and river temperatures over the past few decades across several continents continues to grow (Chessman, 2009; Kaushal *et al.*, 2010; Langan *et al.*, 2001; Morrison *et al.*, 2002; Ormerod, 2009; van Vliet *et al.*, 2011; Webb and Nobilis, 2007), and has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold sternothermic species (Brown *et al.*, 2007; Chessman, 2009; Durance and Ormerod, 2007; Ormerod, 2009). Rising water temperatures are also implicated in changes in the composition of river fish communities (Buisson *et al.*, 2008; Daufresne and Boet, 2007), especially in headwater streams where species are more sensitive to warming (e.g. Buisson and Grenouillet, 2009), and this will probably restrict the distribution of cool-water species such as salmonids within their current range (Bartholow, 2005; Bryant, 2009; Ficke *et al.*, 2007; Hague *et al.*, 2011). While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist *et al.*, 2006) and cool- and warm water species of fish (Tisseuil *et al.*, 2012), there is *high confidence* that range contraction threatens the long term persistence of some fully aquatic species, including mountain-top endemics; e.g. species of spiny crayfish (Parastacidae: *Eustacus*) in eastern Australia (Ponniah and Hughes, 2004).

The surface and epilimnetic waters in many lakes also show increases in temperature over the past four decades, with warming trends detected in North America, Eurasia and Africa (Adrian *et al.*, 2009). Rising temperatures resulting in early onset and increased duration and stability of the thermocline in temperate lakes during summer (Winder and Schindler, 2004) are projected to favor a shift in dominance to smaller phytoplankton (Parker *et al.*, 2008; Yvon-Durocher *et al.*, 2011) and cyanobacteria (Johnk *et al.*, 2008; Paerl *et al.*, 2011; Wiedner *et al.*, 2007), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009);

with impacts to water quality, food webs and productivity (Gyllström *et al.*, 2005; O'Reilly *et al.*, 2003; Parker *et al.*, 2008; Shimoda *et al.*, 2011; Verburg *et al.*, 2003). Emergent aquatic macrophytes are likely to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta *et al.*, 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer *et al.*, 2007), noting that warming may increase species richness in smaller temperate waterbodies, especially those at high altitude (Rosset *et al.*, 2010). While less studied, it has been proposed that tropical ectotherms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high latitude environments, despite lower rates of warming (Deutsch *et al.*, 2008; Hamilton, 2010; Laurance *et al.*, 2011).

There is growing evidence that climate induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (see Box CC-RF; Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g. Australia, California and South Africa), are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães *et al.*, 2007; Hermoso and Clavero, 2011) and floods (Meyers *et al.*, 2010). Shifts in hydrologic regimes in snow-melt systems, including earlier runoff and declining base flows in summer (Stewart *et al.*, 2005; Stewart, 2009), are projected to impact on freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased inter-annual variability will probably increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm *et al.*, 2003), reduction in floodplain egg- and seed-banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Bond *et al.*, 2008; Johnson *et al.*, 2005; Sheldon *et al.*, 2010), and terrestrialization of wetlands (Davis and Thompson, 2010).

Climate induced changes in precipitation will probably be an important factor altering peatland vegetation in temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift from a *Sphagnum* dominated to vascular plant dominated vegetation type and a general decline of C sequestration in the longer term (Limpens *et al.*, 2008). Mire ecosystems (i.e. bogs, transition bogs and fens) in central Europe face severe climate risk, with increased summer temperatures being particularly important (Essl *et al.*, 2012). Declines in precipitation and longer dry seasons in major tropical peatland areas in southeast Asia, are projected to result in lower water tables more often and for longer periods, with an increased risk of fire (Li *et al.*, 2007; Rieley *et al.*, 2008; Frolking *et al.*, 2011).

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on waterbirds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine *et al.*, 2010; Traill *et al.*, 2010) but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas and water (Syvitski *et al.*, 2009; see Chapter 5.3.1.4). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke *et al.*, 2007).

4.3.3.4. Tundra, Alpine, Permafrost Systems

The region of the High Arctic, and its tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman *et al.*, 2009; Hartmann *et al.*, in press. Changes consistent with warming are also evident in the freshwater systems, ecosystems (both plants and animals) and permafrost of the region (Hinzman *et al.*, 2005; Axford *et al.*, 2009; Jia *et al.*, 2009b; Post *et al.*, 2009; Prowse and Brown, 2010; Romanovsky *et al.*, 2010; Walker *et al.*, 2012). Change is widespread , with most of the Arctic experiencing recent change in vegetation photosynthetic capacity and other aspects, particularly in areas adjacent to areas of the Arctic with rapidly retreating sea ice (Bhatt *et al.*, 2010).

There is *high confidence* that continued climate change is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially in the future, with an ongoing expansion in woody vegetation cover

projected in tundra regions over the 21st Century in the CMIP5 Earth System Models (Ciais *et al.*, in press) by dynamic global vegetation models driven by other climate model projections, and by observationally-based statistical models (Pearson *et al.*, 2013). Changes may be complex (see Box 4-4) and in some cases involve non-linear and threshold responses to warming and other climatic change (Hinzman *et al.*, 2005; Mueller *et al.*, 2009b; Bonfils *et al.*, 2012). Due to long response times of vegetation to both warming and increased CO_2 (Ciais *et al.*, in press; Falloon *et al.*, 2012) Earth System Models project Arctic vegetation change to continue long after any stabilization of global mean temperature. In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized global radiative forcing due to greenhouse gases (Falloon *et al.*, 2012).

In the arctic tundra biome, vegetation productivity has systematically increased over the past few decades, as documented across a range of scales in both North America and northern Eurasia – from the plot level (Myers-Smith *et al.*, 2011; Elmendorf *et al.*, 2012) to the region (Stow *et al.*, 2007) to continental (Jia *et al.*, 2009b) and the circumpolar arctic (Goetz *et al.*, 2007; de Jong *et al.*, 2011). This phenomenon is amplified by retreat of coastal sea ice (Bhatt *et al.*, 2010) and has been widely discussed in the context of increased shrub growth consistent with documented shrub expansion over the last half century through repeat photography and satellite observations (Forbes *et al.*, 2010; Myers-Smith *et al.*, 2011). Deciduous shrubs (i.e., dwarf birch, alder and willow species), in particular, respond to warming with increased growth (Euskirchen *et al.*, 2009; Lantz *et al.*, 2010), but this response is shared with other plant functional types, particularly graminoids (Walker, 2006; Epstein, 2008). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated areas (Jia *et al.*, 2009b; Beck and Goetz, 2011), thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. Shrub expansion and height changes remain particularly important, however, because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm *et al.*, 2005; Lawrence *et al.*, 2007; Bonfils *et al.*, 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III *et al.*, 2005; Blok *et al.*, 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils *et al.*, 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi *et al.*, 2007; Bonfils *et al.*, 2012).

The arctic tundra biome is also experiencing shifts in two additional phenomena; fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid "leap-frogging" to areas reinitialized by burning (Epstein *et al.*, 2007; Goetz *et al.*, 2011). When already present at the boreal-tundra ecotone, even sparsely, shrub and tree species show increased productivity with warmer conditions (Devi *et al.*, 2008; Andreu-Hayles *et al.*, 2011; Elmendorf *et al.*, 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack *et al.*, 2011; Rocha and Shaver, 2011) but also increase active layer depth during summer months (Racine *et al.*, 2004; Liljedahl *et al.*, 2007) and produce thermokarsting associated with thawing of ice-rich permafrost. There is tremendous variability in the degree of thermokarsting associated with fire disturbance, depending upon the substrate and ice content (Jorgenson *et al.*, 2010) but the combination of thermokarsting and seasonal cryoturbation create conditions that alter vegetation succession (Racine *et al.*, 2004; Lantz *et al.*, 2009; Higuera *et al.*, 2011).

There is *high confidence* that the area of permafrost is projected to continue to decline over the first half of the 21st Century in all emissions scenarios (Figure 4-11). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, permafrost area is projected to stabilize at a level approximately 20% below the 20th Century area, and then begin a slight recovering trend. In RCP4.5, in which CO_2 concentration is stabilized at approximately 550ppmv by the mid-21st Century, permafrost continues to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO_2 rise, permafrost area is simulated to approach zero by the middle of the 22nd Century (Figure 4-11).

[INSERT FIGURE 4-11 HERE
Figure 4-11: Simulations of past and future (for three Representative Concentration Pathways - RCPs) northern hemisphere permafrost area with a maximum thaw depth less than 3m deep (Caesar *et al.*, 2012) using the HadGEM2-ES Earth System Model (Jones *et al.*, 2011).]

Frozen soils and permafrost currently hold more than twice the carbon than the atmosphere and thus represent a particularly large vulnerability to climate change (i.e., warming). Although the Arctic is currently a net carbon sink, continued warming will act to soon turn the Arctic to a net carbon source, that will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2, CH_4, and perhaps N_2O, from the terrestrial biosphere into the atmosphere (Schuur *et al.*, 2008; Schuur *et al.*, 2009; Maslin *et al.*, 2010; McGuire *et al.*, 2010; O'Connor *et al.*, 2010; Schaefer *et al.*, 2011). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire *et al.*, 2010; O'Donnell *et al.*, 2011). The rapid retreat of snowcover, and resulting spread of shrubs and trees into areas currently dominated by tundra has also already begun, and will continue to serve as a positive feedback accelerating high latitude warming (Chapin III *et al.*, 2005; Bonfils *et al.*, 2012).

There is *medium confidence* that rapid change in the Arctic is also affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter *et al.*, 2010), and it is expected that the populations of other Arctic animals (e.g., fox and caribou) will be affected dramatically by climate change (Post *et al.*, 2009; Sharma *et al.*, 2009). Simple niche-based, or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to on-going climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline and drying of soils is already causing a large increase in mountain forest mortality, wildfire and other ecosystem impacts (e.g., Westerling *et al.*, 2006; Kelly and Goulden, 2008; Crimmins *et al.*, 2009; van Mantgem *et al.*, 2009; Pederson *et al.*, 2010; Muhlfeld *et al.*, 2011; Schwilk and Keeley, 2012; Park Williams *et al.*, 2012), and disturbance will continue to be an important agent of climate-induced change in this region (Littell *et al.*, 2010). Alpine ecosystems already appear to already be changing in response to climate change in Africa, Tibet, the Alps, the tropics and elsewhere (Cannone *et al.*, 2007, 2008; Lenoir *et al.*, 2008, 2010; Cui and Graf, 2009; Britton *et al.*, 2009; Normand *et al.*, 2009; Chen *et al.*, 2009, 2011; Allen *et al.*, 2010a; Eggermont *et al.*, 2010; Kudo *et al.*, 2011; Laurance *et al.*, 2011; Engler *et al.*, 2011; Dullinger *et al.*, 2012). For example, in a study of permanent plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival vascular plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli *et al.*, 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried *et al.*, 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback in those systems (e.g., Tibet; Cui and Graf, 2009).

_____ START BOX 4-4 HERE _____

Box 4-4. Boreal – Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader arctic region are consistent with earth system model predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-12). Thus far these changes appear to be not so much threshold responses as gradual and systematic shifts across temperature and moisture gradients. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the earth, due at least in part to arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman *et al.*, 2005; Post *et al.*,

2009; Peng *et al.*, 2011; Elmendorf *et al.*, 2012) as well as from satellite observations (Goetz *et al.*, 2007; Beck *et al.*, 2011b; Xu *et al.*, 2013) and captured in earth system models (McGuire *et al.*, 2010).

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, are facilitated by more rapid shifts associated with fire disturbance (Mack *et al.*, 2008; Johnstone *et al.*, 2010). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Ma *et al.*, 2012; Anderegg *et al.*, 2013a; Choat *et al.*, 2012). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by leap-frog dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova *et al.*, 2009; Hampe, 2011; Brown, 2010). In North America these coupled interactions set the stage for changes in ecological processes, already documented, consistent with a biome shift characterized by increased deciduous composition in the interior boreal forest and evergreen conifer migration into tundra areas that are, at the same time, experiencing increased shrub densification. The net feedback of these ecological changes to climate is multi-faceted, complex, and not yet well known across large regions except via modeling studies, which are often poorly constrained by observations.

[INSERT FIGURE 4-12 HERE
Figure 4-12: Tundra-Boreal Biome Shift. Earth system models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates poleward into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra-forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets and net ecosystem carbon balance. Arrows indicate the magnitude of albedo and net ecosystem carbon balance (NECB) for boreal forest and tundra biomes, and albedo for sea ice and open water.]

_____ END BOX 4-4 HERE _____

4.3.3.5. Highly Human-Modified Systems - Plantations, Bioenergy Systems, Urban Ecosystems, Cultural Landscapes

As the majority of ice-free land surface is dominated by highly human modified systems, we assess their vulnerability to climate change particularly for those systems not dealt with elsewhere, i.e. except agriculture (WGII, chapter 7) and fisheries (WGII, chapter 3).

4.3.3.5.1. Plantation forestry

While a majority of general aspects on forests are already dealt with in section 4.3.3.1, here we focus on issues that are specifically relevant to plantation forests. Forest plantations are established through afforestation of recent non-forest land and reforestation of forest land, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010b). With 7%, they currently cover only a minor fraction of the global forest area, and the largest plantation areas exist in Asia, Europe (excl. Russian Federation) and North and South America (FAO, 2010a). However, the area of forest plantations has grown rapidly by about five million ha from 2000 to 2010 (FAO, 2010b). Most recent plantations have been established in the tropics and subtropics, but also in some temperate regions, in particular in China (Kirilenko and Sedjo, 2007; FAO, 2010a), mostly by afforestation of non-forest area (FAO, 2010b).

In most areas with forest plantations, forest growth rates have generally increased during the last decades - in Europe also because of formally more intensive harvesting (Ciais *et al.*, 2008; Lindner *et al.*, 2010), but the variability is large, and in some areas production has decreased (see 4.3.3.1). In forests that are not highly water-limited, these trends are consistent with higher temperatures and extended growing seasons, but, as in the case of forests in general, clear attribution is difficult because many environmental drivers and changes in forest management interact (*e.g.* Boisvenue and Running, 2006; Ciais *et al.*, 2008; Dale *et al.*, 2010; see also 4.3.3.1).

Regarding future climatically driven changes, results from several studies with forest yield models suggest increases in forest production (Kirilenko and Sedjo, 2007), but these results may be overly optimistic because many models may overestimate potential positive effects of elevated CO_2 (Kirilenko and Sedjo, 2007; see 4.2.4.4) and the effects of disturbances, such as wildfires, forest pests, pathogens and windstorms, which are major drivers of forest dynamics, are often either poorly or not at all represented (Kirilenko and Sedjo, 2007). Using a model that accounts for fire effects and insect damage, Kurz *et al.* (2008), for example, showed that recent insect outbreaks might have caused a transition in the Canadian forest sector from a sink to a source of carbon. Future projections for particular stands or regions are also uncertain because results from different models often differ substantially, both regarding forest productivity (*e.g*. Sitch *et al.*, 2008; Keenan *et al.*, 2011) and potential species ranges (see 4.3.3.1.2). Nevertheless, decreased production is expected in particular in already dry forest regions for which further drying is projected, such as the south-western U.S. (Williams *et al.*, 2010a), and extreme drying might also decrease forest yields in currently not water-limited forests (*e.g.* Sitch *et al.*, 2008; see 4.3.3.1). Plantations in cold-limited areas could benefit from climate change and their productivity could increase if associated changes in disturbances, pests and pathogens do not outweigh the potential positive climatic effects.

Many plantation forests are monospecies stands or sometimes even include only a limited number of clones of one species. In the temperate and boreal zone, native species are commonly used (but in some cases beyond their native range), while in the tropics, conventional tree planting is mainly based on exotic species from a few genera such as *Pinus*, *Eucalyptus* and *Acacia* grown in single-species stands. Low species (and often also genetic) diversity compared with natural stands might render plantation forests particularly vulnerable to climate change (*e.g*. Hemery, 2008). Choosing provenances that are well adapted to current and future climates is extremely difficult because of uncertainties in climate projections (Broadmeadow *et al.*, 2005). Furthermore, it is highly uncertain how forest pests and pathogens will spread as a result of climate change and trade and new pathogen-tree interactions might occur (e.g. Brasier and Webber, 2010). Nevertheless, adaptive forest management can decrease the vulnerability of plantations to climate change (Hemery, 2008; Bolte *et al.*, 2009; Seppälä, 2009; Dale *et al.*, 2010. For example, risk spreading by promoting multi-species mixed stands and natural regeneration, which can increase genetic diversity (Kramer *et al.*, 2010), has been advocated as a plausible adaptation strategy for temperate forests (Hemery, 2008; Bolte *et al.*, 2010). Also in the tropics, recent approaches highlight the use of native species in mixed stands (Erskine *et al.*, 2006; Petit and Montagnini, 2006; Hall *et al.*, 2011), but missing information on the ecology of many of the tropical tree species and little experience in managing mixed tropical tree plantations remains to be a major problem (Hall *et al.*, 2011). At least at the southern border of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson *et al.*, 2008; Bolte *et al.*, 2010).

4.3.3.5.2. Bioenergy systems

Bioenergy sources include traditional forms such as wood and charcoal and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less-developed parts of the world, such as Africa, and retain a niche in developed countries. The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation policies that incentivise their use, or as a strategy to decrease oil dependence and thus increase energy security (Cochrane and Barber, 2009). The WG III chapter on energy addresses their potential as a climate mitigation strategy, while the sensitivity of biofuel crops to climate change should be quite similar to those previously mentioned for plantation forestry (which to a large extent are grown for bioenergy purposes) and/or agricultural systems (WGII, chapter 7). In a review on climate change impacts on biofuel yields in temperate environments (Luckman and Kavanagh, 2000) it was concluded that elevated CO_2 might contribute to increase drought tolerance of bioenergy crops (as it is paralleled by improved plant water use), which may lead to constantly high yields. Generally, potentials of bioenergy production under climate change might be high, but are very uncertain (Ma and Zhou, 2012).

An important part to deal with here is the ecosystem impacts of large-scale land-use changes related to the growing of bioenergy biofuels. Policy shifts in OECD countries favor the expansion of biofuel production, sometimes at the expense of food crop production, and placing new pressures on terrestrial and freshwater ecosystems (Searchinger *et*

al., 2008; Lapola *et al.*, 2010). It is, for example, unclear if the global trend to reduced forest loss will continue - there are substantial pressures to deforest for the production of food and biofuels (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011). Moiseyev *et al.*, (2011) found that in a 20 years perspective it is very little difference between the IPCC scenarios A1 and B2 regarding harvest level in Europe, and that the EU RES policy may only moderately influence the EU forestry and forest industries as long as the wood price paid by the bioenergy producers are below 50-60 US$ per m^3 wood. Under the assumption of doubling the growth rate of demand for bioenergy until 2030, a scenario by Martin *et al.* (2010) would lead to severe consequences for the global forest sector with a global reduction of forest stocks of 2 % or a 4% reduction for Asia.

Bioenergy potentials are strongly influenced by human food requirements (incl. feed required for livestock), thus integrated approaches to optimize food and bioenergy are needed (Ma and Zhou, 2012). Such considerations ignore areas for the conservation of biodiversity and ecosystems. These are more explicitly dealt with by McAlpine *et al.* (2009) and Millar *et al.* (2004), while in both papers the usage of abandoned land, which was previously under agricultural use, is regarded as an option for biomass production which reduces net warming. However, this ignores for example that such habitats may be core elements in cultural landscapes of high conservation value (many species rich grasslands in Europe have been croplands before and later abandoned), and that the productivity of such areas could be too limited for biofuels (Mishra *et al.*, 2010). As an alternative, Fargione (2011) discusses biofuel crop yield increases on existing cropland, with the aim to avoid expansion of agriculture.

4.3.3.5.3. Cultural landscapes

"Cultural landscapes are at the interface between nature and culture, tangible and intangible heritage, biological and cultural diversity—they represent a closely woven net of relationships, the essence of culture and people's identity" (Rössler, 2006, p. 334). They are characterized by a long history of human-nature interactions, where man is the main driver and has often created open landscapes, rich in structures and often also in species. A UNESCO Flagship programme focusses especially on cultural landscapes (Rössler, 2006). These landscapes nowadays are often about to lose their roles as recreational species rich entities due to agricultural intensification and extensification (Huntington *et al.*, 2012). Well researched examples are grassland or mixed agriculture landscapes in Europe or rice landscapes in Asia (Kuldna *et al.*, 2009), while such landscapes may well exist across the globe (e.g., Rössler, 2006; Heckenberger *et al.*, 2007).

In such landscapes, conservation efforts - as all across the globe - often focus on the conservation of ecosystems that contain endangered biotic communities. However, in such cultural landscapes this aim might be hard to achieve due to the very dynamic nature of systems. Keeping species in a favorable conservation status in cultural landscapes (one aim e.g. of European policies; EU Council, 1992), can normally only be achieved through appropriate management, as the vast majority of endangered species in the wider countryside depend on certain types of land use for their survival. This requires profound knowledge of the systems and species involved, and as this is rarely the case, conservation success was limited (see Kirdyanov *et al.*, 2012 for a notable exception).

As in many other cases, population and niche models are available and partly already validated (Kirdyanov *et al.*, 2012). This shows where future challenges are to be found: particularly in the quantification of relative importance of climate change in comparison with the habitat and its management (Settele and Kühn, 2009). So far the majority of changes can be attributed to land use as the most obvious driver (Nowicki *et al.*, 2007), while the impact of climate change can be readily detected in few examples (Devictor *et al.*, 2012), combined effects seem to better explain the overall picture (Schweiger *et al.*, 2008; Schweiger *et al.*, 2012), where attribution to climate change seems low to medium. As a consequence, it has been suggested to adjust the European Natura 2000 protected area network to take into account changing climatic conditions and to enable migration or dispersal of species across the landscape (Heubes *et al.*, 2011; Jin *et al.*, 2010).

4.3.3.5.4. Urban ecosystems

Over half of humanity lives in urban areas (see for definition in chapter 8) with a yearly increase of ca. 74 million people (United Nations *et al.*, 2012). Although urban areas cover only ca. 0.5 % of Earth's terrestrial surface (Schneider *et al.*, 2009) they harbor a large variety of species (McKinney, 2008). Urban areas are themselves drivers of climatic change as they are accounted for a significant proportion of total anthropogenic greenhouse gas emissions (Satterthwaite, 2008) and many urban centers are also heavily impacted by increased minimum and sometimes decreased maximum air temperatures, reduced or increased precipitation and altered biogeochemical cycles (Grimm *et al.*, 2008). An important threat to cities comes from extreme events. Many cities are located at coasts or rivers. However since there is *medium confidence* (based on physical conditions) that projected increases in heavy rainfall events would contribute to increases in local flooding (IPCC, 2012) there is *limited evidence* that urban areas will be over-proportionally affected by floods in the future, however, it is *very likely* that sea level will contribute to rise in future and hence affect coastal urban areas (IPCC, 2012). For the future it is *virtually certain* that the frequency and magnitude of warm days and nights (heat waves) will increase globally (IPCC, 2012). However Leonelli *et al.* (2011) projected with the integration of an urban land-surface model in the HadAM3 Global Climate Model a significant higher increase in the frequency of hot nights in urban areas compared to rural areas. Hence also the social aspects in urban areas (health status, outdoor activities) and urban infrastructures will be increasingly affected (IPCC, 2012). There is *high agreement* among scientists that urban climate effects (e.g., increased temperatures) nowadays are similar to projected changes of climatic variables at a local scale. Similar to all other ecosystems, ecological impacts of changing climatic factors in urban ecosystems will change species compositions as well as compositions of traits. Knapp *et al.* (2008b) found that traits compositions of urban plant communities are changing during urbanization towards adaptive characteristics of dry and warm environments. With increasing temperatures, this effect might to continue also in the future and will hence be exacerbated compared to non-urban surroundings. Urban areas are one of the main starting points for the establishment and dispersal of alien species (e.g. for plants through urban gardening; Li *et al.*, 2009). With increasing air temperatures especially in winter time and the warming effect of urban areas, the number of established alien plants in urban areas might increase (see also 4.2.4.6.). With increasing numbers of alien species, also the BVOC (Biogenic Volatile Organic Compounds) emissions from gardened alien plants will increase (Lloyd and Fastie, 2003; see also 4.2.4.6.).

4.3.4. Impacts on Key Services

Ecosystem services are the benefits which people derive from ecosystems [see glossary]. The classification system proposed by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2003) is widely used. It recognises *provisioning services* such as food, fiber and water (also known as 'goods' in the economic literature, and which have their own chapters in this assessment); *regulating services* such as climate regulation, pollination, pest and disease control and flood control; *supporting services* (habitat services in TEEB) which are used by people indirectly, through other services, and include items such as primary production and nutrient cycling; and *cultural services* which include recreation, aesthetic and spiritual benefits. The list of ecosystem services is long and growing; and almost all are potentially vulnerable to climate change. The provisioning services are comprehensively dealt with in chapter 3 and chapter 7, and the tourism-based services in chapter 13. This chapter focusses on those regulating services where the link to climate change has been examined.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing i) shifts in habitat distribution that are not followed by species, ii) shifts in species distributions that move them outside of their preferred habitats and iii) changes in habitat quality (Urban *et al.*, 2012; Dullinger *et al.*, 2012). There is some evidence that these climate change impacts have already occurred. For example, loss of sea ice is altering habitats for polar bears and may partially explain declines in polar bear populations in some area (see also Chapter 28). However, this is not yet a widespread phenomenon. Models of future shifts in biome, vegetation type and species distributions, on the other hand, suggest that many species could be outside of their preferred habitats with the next few decades due to climate change (Urban *et al.*, 2012).

Hole *et al.* (2009) report that the majority of African birds are projected to move large distances over the next 60 years resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa) and migration across unfavorable habitats. Many birds may find suitable climate in the large network of protected areas, but will be forced to cope with new habitat constraints. Similarly, Araujo *et al.*, 2011) indicate that approximately 60% of plants and vertebrate species would no longer have favorable climates within European protected areas, often pushing them into unsuitable or less preferred habitats. Wiens *et al.* (2011) project similar effects in the western US, but also find that climate change may open up new opportunities for protecting species in areas where climate is currently unsuitable. Indeed, in some changes climate change may allow some species to move into areas of lower current or future land use pressure including protected areas (Bomhard *et al.*, 2005). These and other studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species.

Over sufficiently long periods, biomes or habitat types may shift their distributions or disappear entirely due to climate change. Non-analog climates are projected to occur in the future (Williams *et al.*, 2007b; Wiens *et al.*, 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (section 4.2.2). The impacts of this on species abundance and extinction risk is difficult to evaluate because species may show substantial capacity to adapt to novel habitats (Prugh *et al.*, 2008; Willis and Bhagwat, 2009; Oliver *et al.*, 2009). This high uncertainty in habitat specificity for many species means it is not possible to predict if species extinctions due to climate induced loss of habitat will be below or far above current extinction rates caused by non-climate factors (Malcolm *et al.*, 2006). This does, however, also reinforce the idea that habitat quality across all components of landscapes will increase in importance for biodiversity conservation in the future.

Effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. However, several recent studies indicate that climate change may have and probably will alter habitat quality (Iverson *et al.*, 2011; Matthews *et al.*, 2011). For example, climate change induced changes in habitat quality due to decreasing snowfall may partially explain declining songbird populations in southwestern US (Martin and Maron, 2012).

4.3.4.2. Pollination, Pest and Disease Regulation

It can be inferred that global change will result in new communities (Schweiger *et al.*, 2010). As these will have experienced a much shorter (or even no) period of coevolution, drastic changes of ecological interactions like shifts in the use of certain plants by herbivores, in the range of prey of predators or in pollination networks are to be expected (Tylianakis *et al.*, 2008; Schweiger *et al.*, 2012). This might generally result in drastic changes in the provision of services (Montoya and Raffaelli, 2010).

Among the regulating services most strongly related to biodiversity, pollination and biocontrol of pests have to be highlighted. Climate change tends to increase the abundance of pest species particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced, e.g. through the quality of food plants (Payette and Filion, 1985) or via the effects on their natural enemies (predators and parasitoids). Direct impacts are via the relatively high temperature optima of insects, which lead to increased vitality and reproduction (Allen *et al.*, 2010a). Mild winters in temperate areas promote frost susceptible pests. For the vast majority of indirect effects, e.g. spread of insect borne diseases, information is scarce (for further assessments on climate change effects on pest and disease dynamics see WGII, chapters 7 and 11).

Climate change, after land-use changes, can be regarded as the second most relevant factor responsible for the decline of pollinators (Potts *et al.*, 2010; for other factors see Biesmeijer *et al.*, 2006; Brittain *et al.*, 2010a; Brittain *et al.*, 2010b). While the potential influence of climate change on pollination can be manifold (compare Hegland *et al.*, 2009; Roberts *et al.*, 2011; Schweiger *et al.*, 2010), there are only few observations which mostly relate to the de-coupling of plants and their pollinators – especially in relation to phenology (Gordo and Sanz, 2005). While Peñuelas and Boada (2003) states that these phenological effects may be less than feared, an analysis of

phonological observations in plants Wolkovich *et al.* (2012) shows that experimental data on phenology may grossly underestimate phenological shifts. As Willmer's (2003) view is partly based upon experimental observations, it has to be seen whether field evidence might proof something different (compare Phenology Chapter 4.3.2.1.).

In relation to honeybees Le Conte and Navajas (2008) state that the generally observed decline is a clear indication for an increasing susceptibility against global change phenomena, with pesticide application, new diseases and stress (and a combination of these) as the most relevant causes. Climate change might contribute by modifying the balance between honeybees and their environment (incl. diseases). Honeybees also have shown a large capacity to adjust to a large variety of environments and their genetic variability should allow them to also cope with climatic change , that's why the preservation of genetic variability within honeybees is regarded as a central aim to mitigate climate change impacts (Le Conte and Navajas, 2008).

4.3.4.3. Climate Regulation Services

Ecosystems moderate the local climate through a range of mechanisms, including reducing the near-ground wind velocity, cooling the air through shading and the evaporation of water and ameliorating low temperatures through releasing heat absorbed during the day or summer. This service is widely recognized and valued, for instance in the establishment of windbreaks, gardens and urban parks. The focus of this section is on processes operating at much larger scales – the region to the whole globe. Terrestrial ecosystems affect climate at large scales through their influence on the physical properties of the land surface and on the composition of the atmosphere with respect to radiatively-active gases and particles. In the decade 2000-2010, approximately one fourth of the CO_2 emitted to the atmosphere by human activities was taken up by terrestrial ecosystems, reducing the rate of climate change proportionately (4.3.2.3, WG 1 Chapter 6).

One study (Arora and Montenegro, 2011) suggests that the overall effect of tropical afforestation on global temperature is up to 75% greater than would be expected on the basis of increased carbon storage alone, due to physical processes such as changes in evapotranspiration; but in other circumstances the cooling due to land-cover change may be *less* than that estimated from carbon uptake alone, due to decreased albedo (4.2.4.1). Observations and model evidence indicates that, broadly speaking, forests make warm areas cooler and cold areas warmer, through the competing effects of evapotranspiration (cooling) and surface albedo (in dark-canopied forests, generally warming). Model simulations suggest that if more than 40% of the pre-1700 extent of the Amazon forest were to be cleared, rainfall in the region would be reduced (Sampaio *et al.*, 2007). According to satellite observations, the effect of conversion of the Brazilian savannas (*cerrado*) to pasture is to induce a local warming, (Loarie *et al.*, 2011), which is partly offset when the pasture is converted to sugarcane. It has been suggested (Ridgwell *et al.*, 2009) that planting large areas of crop varieties with high-albedo leaves could help regional cooling. Model analysis indicates this strategy could be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes, and measurements show that the current range of leaf albedo in major crops is insufficient to make a meaningful difference (Doughty *et al.*, 2011).

4.3.4.4. Potable Water Supply

Freshwater systems provide a range of ecosystem services that benefit society and are *likely* to be affected by climate change (see Table 4-1; Palmer and Filoso, 2009). Many of the implications of climate change on the provisioning services of water for food production and domestic supply are discussed in detail in WGII Chapter 3. Over 80% of the world's population is currently exposed to high levels of threat to water security because of land use change, pollution and water resource use (Vörösmarty *et al.*, 2010). Under climate change, reliability of surface water supply is *likely* to decrease due to increased temporal variations of river flow that are caused by increased variability in precipitation and decreased snow/ice storage (see WGII Chapter 3). In some Mediterranean regions, e.g. the southwest of Western Australia, significant reductions in surface flows have already forced governments to pursue alternative water sources (desalination, recycled wastewater) (see http://www.watercorporation.com.au/watersupply/index.html). In snow dominated regions, warming will mean that less winter precipitation falls as snow and melting of winter snow occurs earlier in spring (*high confidence*; Barnett

et al., 2005). This means a shift in peak discharge to winter and early spring and away from summer and autumn when human demand is highest. In some locations, water storages may not be sufficient to capture winter runoff, particularly if they are also used to safeguard downstream communities from flooding (Barnett *et al.*, 2005). Climate change not only poses risks to the quantity of water available for human society but also the quality. Warming will exacerbate many of the symptoms of eutrophication, including the increased frequency and intensity of harmful cyanobacterial blooms (Paerl and Paul, 2012). Reduced summer flows in rivers increases residence time for algal growth, increases the risk of low dissolved oxygen events and associated poor water quality, and limits the ability to dilute pollution from point sources (Jeppesen *et al.*, 2010).

4.4. Adaptation and its Limits

Wild organisms and ecosystems can adapt to climate change to some degree using intrinsic mechanisms such as migration, change in behavior and evolution: this is known as autonomous adaptation. These mechanisms rely on the availability of suitable habitat and a clear pathway to it; climate change that is sufficiently gradual to allow response by all organisms; and the retention of genetic variability. There are also biological limits to the magnitude of change which can be adapted to; for instance the tolerable body temperature of all warm-blooded animals falls within a narrow range (Clarke and Rothery, 2008). Where autonomous adaptation mechanisms are inadequate, human-assisted adaption is indicated as a supplementary approach.

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see glossary) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit *et al.*, 2000); also called 'spontaneous adaptation' (Smit *et al.*, 2007). In the context of human systems it is sometimes referred to as 'coping capacity'. The capacity for autonomous adaptation is necessary for resilience but is not synonymous with that term as it is now used (Walker *et al.*, 2004). Here we focus on adaptation to a changing climate in all its manifestations, recognizing that climate change in the narrow sense is necessarily associated with changing CO_2 and ozone, and in practice is usually accompanied by changing land use, abundance of competing or mutualistic organisms and other environmental stressors, such as pollution.

All systems have some capacity for autonomous adaptation, or they would not exist at all. Ecosystems which have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability which they have experienced in the past. Adaptability to one set of challenges does not automatically confer greater adaptive capacity to a different set of challenges, especially if those challenges are novel (i.e. outside the range of experience of the system). Furthermore, an environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously-demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft *et al.*, 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behavior, phenology or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, either through in- or out-migration, or local extinction.

4.4.1.1. Phenological and Physiological

The ability to project future impacts of climate change on ecosystems is complicated by the potential for adaptations by species, which may alter apparent relationships between climate variables and species / ecosystem viability. Adaptation by individual species may increase their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin *et al.*, 2007), but may also affect their interdependence with other species leading to disruption of community interactions (Visser and Both, 2005).

Phenology is typically highly adapted to the climate seasonality of the environment in which the organism evolved. The phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species and pollinators. Thus change in phenology is a sensitive indicator of adaptation (Menzel *et al.*, 2006), but also a potential mechanism of ecosystem disruption if adaptation is insufficiently rapid or coordinated between interdependent species, or is cued to environmental signals that are not affected by climate change, such as day-length (Bradley *et al.*, 1999; Both and Visser, 2001; Parmesan, 2006). The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, late-succession temperate trees require a chilling period in winter, followed by a threshold in daylength, and only then are sensitive to temperature. As a result, projecting current phenological trends forward is risky, since the relative importance of cues can change (Cook *et al.*, 2012). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky mountains to frost as a result of earlier snowmelt (Inouye, 2008).

The importance of adaptation and potential for disruption from different rates of phenological change are illustrated by the consequences of timing of migratory bird activities (see 4.3.2.1.). Breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100 European migratory bird species, those that advanced their arrival showed stable or increasing populations, while that did not adjust their arrival date on average showed declining populations (Møller *et al.*, 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) over two decades, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, unlike areas with a later food peak which can still be exploited by early-breeding birds (Both *et al.*, 2006). Selection for earlier laying dates has been shown to stronger in warmer years when food supply (caterpillars) peaked early (Coppack and Both, 2002). Systematic cross-taxa studies in the USA and UK indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook *et al.*, 2008; Thackeray *et al.*, 2010).

It has been suggested that shorter generation times would give greater opportunity for autonomous adaptation through natural selection (Rosenheim and Tabashnik, 1991; Bertaux *et al.*, 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time only had limited influence (Thackeray *et al.*, 2010).

The physiological processes in organisms can either adapt through plasticity or genetically (i.e., through evolution). The former is generally regarded as rapid but limited, and the latter as less constrained, but slow (see 4.4.1.2) although long-term studies of a few organisms indicate rapid genetic adaptation to a changing climate (Bradshaw and Holzapfel, 2006). Acclimation to higher temperatures and/or higher CO_2 concentrations is seen in many organisms, but to very widely varying extents and general understanding remains limited (Hofmann and Todgham, 2010). A physiological process with large potential consequences for the global carbon cycle and thus the climate system is the sensitivity of the relationship between organism temperature and respiration rate, particularly in decomposer organisms (Jones *et al.*, 2003). The shape of the relationship varies between locations with different climates and shows apparent acclimation within months or years to a changing climate (Giardina and Ryan, 2000; Luo *et al.*, 2001; Rustad, 2001). The relationship is also dependent on C substrate type and the presence of other respiration-controlling environmental factors, complicating the determination of the inherent rate and its adaptation to a changing climate. Several competing hypotheses can explain the observed reduction in respiration rates in soil warming experiments after an initial peak – physiological adaptation; depletion of readily available substrate (Kirschbaum, 2004); and varying temperature sensitivities in different soil carbon pools (Knorr *et al.*, 2005).

4.4.1.2. Evolutionary and Genetic

Since the AR4 report there has been substantial progress in defining the concepts and tools necessary for documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred to as "rapid evolution". Evolution can occur through many mechanisms including selection of existing resistant genes or genotypes within populations, hybridization, mutation and selection of new adaptive genes and perhaps

even through epigenetics (Chevin *et al.*, 2010; Chown *et al.*, 2010; (Lavergne *et al.*, 2010; Paun *et al.*, 2010; Hoffmann and Sgro, 2011; Anderson *et al.*, 2012b; Donnelly *et al.*, 2012; Franks and Hoffmann, 2012; Hegarty, 2012; Merilä, 2012; Bell, 2013; Zhang *et al.*, 2013). Mechanisms such as selection of existing genes and genotypes, hybridization and epigenetics can lead to adaptation in very few generations, while others, notably mutation and selection of new genes, typically take at least many tens of generations. This means that species with very fast life cycles, e.g., bacteria, should in general have greater capacity to respond to climate change than species with long life cycles such as large mammals and trees. Unfortunately, there remains a paucity of observational or experimental data that can be used for detection and attribution of climate signals and for validation of models and theory.

Observed Evolutionary and Genetic Responses to Rapid Changes in Climate - There is a small, but growing body of observational evidence supporting studies reviewed in the AR4 report that some species have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants - Franks and Weis, 2008; Anderson *et al.*, 2012a; Hill *et al.*, 2011; vertebrates - Ozgul *et al.*, 2010; Husby *et al.*, 2011; Phillimore *et al.* (2010; Karell *et al.*, 2011; insects - Buckley *et al.*, 2012; van Asch *et al.*, 2012). For example, Karell *et al.* (2011) found increasing numbers of brown genotypes of the tawny owl in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the heritable white genotype. Phillimore *et al.* (2010) showed for the common frog in Britain, that population differences in earlier spawning due to increasing spring temperatures could be attributed largely to local genetic adaptation. Using a combination of models and observations Visser and colleagues have built a case for detection and attribution of genetic adaptation in an insectivorous bird (Husby *et al.*, 2011), and in a herbivorous insect that has tracked warming related changes in the budburst timing of its host tree (van Asch *et al.*, 2012). In contrast, many species appear to be maladapted to changing climates or to respond to recent warming through phenotypic plasticity, in part because factors such as limited standing genetic variation, weak heritability of adaptive traits or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen *et al.*, 2011; Ketola *et al.*, 2012; Mihoub *et al.*, 2012; Merilä, 2012). Most studies of rapid evolution suffer from methodological weakness making it difficult to clearly demonstrate a genetic basis underlying observed phenotypic responses to environmental change (Gienapp *et al.*, 2008; Franks and Hoffmann, 2012; Hansen *et al.*, 2012; Merilä, 2012). When combined with recent progress on conceptual frameworks, rapid advances in quantitative genetics, genomics and phylogenetics will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis *et al.*, 2010; Salamin *et al.*, 2010; Hoffmann and Sgro, 2011).

The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be inferred from the degree to which environmental niches are conserved when environment is changed. There is good evidence that environmental niches are conserved for some species under some conditions (plants - Petitpierre *et al.* (2012; birds - Monahan and Tingley, 2012; review - Peterson *et al.*, 2011), but also evidence suggesting that environmental niches can evolve over time scales of several decades following invasion or changes in climate (Broennimann *et al.*, 2007; Angetter *et al.*, 2011; Konarzewski *et al.*, 2012; Leal and Gunderson, 2012; Lavergne *et al.*, 2013). The paleontological record also provides insight into past evolutionary response in the face of natural climate variation. In general, environmental niches appear to be broadly conserved through time although there is insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in population size (Peterson *et al.*, 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and could also play a key role in future adaptation (Soliani *et al.*, 2012; Hegarty, 2012). There is also new evidence that epigenetic mechanisms, such as DNA methylation, can play a role in heritable and potentially very rapid adaptation to climate (Paun *et al.*, 2010; Zhang *et al.*, 2013), but understanding of these mechanisms is too preliminary to know how important they are for adaptation to climate change.

Mechanisms Mediating Rapid Evolutionary Response to Future Climate Change - Studies of extent genetic variability across species ranges and models that couple gene flow with spatially-explicit population dynamics suggest that populations may respond to climate change in ways that are counterintuitive. In some cases, too much or too little gene flow to populations at range margins may have created fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle *et al.*, 2010; Hill *et al.*, 2011). Conversely, there is also evidence from experiments, models and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those

at range boundaries (Bell and Gonzalez, 2009). Generalization will be complicated by the interactions between local adaptation, gene flow and population dynamics (Bridle *et al.*, 2010).

Substantial progress has been made since the AR4 report in developing models that can be used to explore whether genetic adaptation will be fast enough to track climate change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to significantly attenuate negative impacts of future climate change (Kuparinen *et al.*, 2010; Kremer *et al.*, 2012), which is coherent with observations and experiments (Jump *et al.*, 2006, Jump *et al.*, 2008). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected rates of climate change, in large part due to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp *et al.* (2013) found that modeled breeding times tracked climate change, but only at low to moderate rates of change. For a species with an even faster life cycle, van Asch *et al.*, (2007, 2012) predicted that rapid evolution of the phenological response of a herbivorous insect should have allowed it to track recent warming, which it has. This suggests substantial capacity for future adaptation in this insect since current and moderate future rates of future climate change are similar. Kearney *et al.* (2009) on the other hand found that rapid evolutionary responses only modestly affected modeled range shifts in a mosquito species in response to climate change. More broadly, Walters *et al.* (2012) found that modeled extinction risk in ecotherms - species that do not internally regulate their body temperature - is substantially reduced by genetic adaptation at rates of climate change that are roughly less than 0.02°C per generation. Based on these assumptions, species with short generation times such as most insects potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change (Figure 4-6), but species with longer generation times could be at risk of extinction at moderate to high rates of climate change. Recent experimental work on "evolutionary rescue" shows that long-term avoidance of extinction through genetic adaptation to hostile environments can occur under certain conditions (Bell, 2013). Generalizations coming from experiments and theoretical work are that evolutionary rescue requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size and range contractions over many generations before population recovery (Bell, 2013; Schiffers *et al.*, 2013). Model-based projections must, however, be viewed with considerable caution because there are many evolutionary and ecological mechanisms that can either speed up or inhibit heritable adaptation to climate change that are not accounted for in most models (Cobben *et al.*, 2012; Norberg *et al.*, 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of enhanced maladaptation to climate change and more rapid population declines under certain conditions (Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change, but the extent to which it contributes to adaptive capacity depends a great deal on the costs of plasticity in terms of fitness (Chevin *et al.*, 2010). High plasticity in the face of climate change that has low costs can greatly improve the odds of adapting to climate change; however, plasticity that has high fitness costs can have much more modest effects on the odds of adaptation.

The AR4 report concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)". Work since then provides a similar, but more nuanced view of rapid evolution in the face of climate change. There are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* across all species). The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism and models showing limited adaptive capacity especially in species with long generation times, all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures and potentially impacting ecosystem functioning and services.

4.4.1.3. Migration of Species

This mode of adaptation has been extensively dealt with in section 4.3.2.5. It is anticipated that the movement of species – individually and collectively – will continue in response to shifting climate patterns. Its effectiveness as an adaptation mechanism is constrained by three factors. First, the rate of migration for many species, in many regions of the world, is slower than the rate of movement of the climate envelope (see Figure 4-6). Second, the ecosystem interactions can only remain intact if all parts of the ecosystem migrate simultaneously and at the same rate. Thirdly, the contemporary landscape and drainage systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements and dams.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate, external intervention with the intent of increasing the capacity of the target organism, ecosystem or social-ecological system to survive and function at an acceptable level in the presence of climate change (see glossary) It is also known as 'planned adaptation' (Smit *et al.*, 2007). This chapter focuses less on the adaptation of people, human communities and infrastructure, since they are the topics of WGII chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. "Assistance" in this context means a range of actions, from ensuring the presence of suitable habitat and dispersal pathways and the reduction or removal of other stressors, to physically moving organisms, storing them and establishing them in new places. In addition to the other approaches assessed in this section, "Ecosystem-based Adaptation" provides an option that integrates the use of biodiversity and ecosystem services into climate change adaptation strategies in ways that can optimize co-benefits for local communities and carbon management, as well as reduce the risks associated with possible maladaption (see Box CC-EA). Note that there are risks associated with all forms human-assisted adaptation (see 4.4.4), particularly in the presence of far-from-perfect predictive capabilities (Willis and Bhagwat, 2009).

4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems

The alleviation of other stresses acting on ecosystems is suggested to increase the capacity of ecosystems to survive, and adapt to, climate change, since the effects are generally either additive or compounding. Ecosystem restoration is one way of alleviating such stresses while increasing the area available for adaptation (Harris *et al.*, 2006). Building the resilience of at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection is the core of the adaptation strategy for the Arctic (Christie and Sommerkorn, 2012). 'Ecosystem-based adaptation' is the phrase increasingly used to cover a package of protective and restorative actions aimed at increasing resilience (e.g. Colls *et al.*, 2009).

4.4.2.2. The Size, Location and Layout of Protected Areas

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller and Zavaleta, 2009). This is because for most protected areas, under plausible scenarios of climate change, a significant fraction of the biota will no longer have a viable population within the present protected area footprint. It is noted that the extant geography of protected areas is far from optimal for biodiversity protection even under the current climate; that it is cheaper to acquire land proactively in the areas of projected future bioclimatic suitability than to correct the current non-optimality and then later add on areas to deal with climate change as it unfolds (Hannah *et al.*, 2007)); and that the existing protected area network will still have utility in future climates, even though it may contain different species. Hickler *et al.* (2012) analyzed the layout of protected areas in Europe and concluded that under projected 21st century change and concluded that a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new area that needs to be added to the existing protected area network to ensure future representativeness is situation-specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux *et al.*, 2008); regional scale planning is more effective than treating each local case

independently (Heller and Zavaleta, 2009); since it is the network of habitats and protected areas that confers resilience rather than any single element; and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009).

4.4.2.3. Landscape and Watershed Management

The general principles for management adaptations in United States were summarized from a major literature review by West *et al.*, 2009. They suggest that in the context of climate change a successful management of natural resources will require cycling between 'managing for resilience'' and ''managing for change". This requires the anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the national level, the necessary changes in practice to facilitate adaptation include: (1) management at appropriate scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3) rational approaches for establishing priorities and applying triage; and (4) management with the expectation of ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital, and (4) information and science.

In 14,000 ha of forested watersheds in central Nova Scotia, Canada, the adaptation to climate change was assessed using the landscape disturbance model LANDIS-II, (Steenberg *et al.*, 2011). The study simulated the impact of three components of timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives.

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change, (Hoegh-Guldberg *et al.*, 2008; Vitt *et al.*, 2010; Chmura *et al.*, 2011; Loss *et al.*, 2011). The options for management can be summarized as: i) try to maintain or improve existing habitat so that species don't have to move, ii) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson *et al.*, 2012), or iii) intervene heavily by translocating species (Hoegh-Guldberg *et al.*, 2008; Loss *et al.*, 2011). There is *low agreement* in the scientific community whether it is best to increase the resilience of ecosystems to climate change, thus help to preserve existing communities, or to enhance the capacity of ecosystems to transform in the face of the overwhelming forces of species migration and modifications of ecosystem function by climate change.

There is *high agreement* among the scientific and conservation community that maintaining or improving migration corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (Hole *et al.*, 2011; Jongman *et al.*, 2011). This approach has the benefit of improving the migration potential for large numbers of species and is therefore a more ecosystemic approach than assisted migration for individual species. However, observational and modeling studies show that increases in habitat connectivity do not always improve the population dynamics of target species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson *et al.*, 2010; Matthiessen *et al.*, 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg *et al.*, 2008; Loss *et al.*, 2011; Vitt *et al.*, 2009; Willis and Bhagwat, 2009; Hewitt *et al.*, 2011). The speed of 21st century climate change and substantial habitat fragmentation in many areas of the world mean that many species will be unable to migrate or adapt fast enough to keep pace with climate change. If this results in significant reductions in range size it will pose problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional

species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that could potentially require assisted migration that could easily overwhelm funding capacity (Minteer and Collins, 2010).The degree and magnitude of phenotypic responses or genetic adaptation to climate change are very variable among species, making decisions regarding which species should be translocated complex and debatable.

4.4.2.5. Ex Situ Conservation

Conservation of plant and animal genetic resources outside of their natural environment, in gardens, zoos, breeding programmes, seed-banks or gene-banks has been widely advocated as an 'insurance' against both climate change and other sources of biodiversity loss and impoverishment (Khoury *et al.*, 2010). There are many examples of existing efforts of this type, some very large and with global scope (e.g. Millennium Seed Bank, Svalbard vault). The Dixon National Tallgrass Prairie Seed Bank is an example of prioritization of species for seed banking, both for restoration purposes and for potential assisted migration in the future (Leishman *et al.*, 2007). A genome scan approach identified four potentially adaptive loci in important grassland species *Arrhenatherum elatium.* Knowledge on adaptive loci might in the long run also help to adapt ecosystems to adverse climate change effects through assisted migration of ecotypes rather than introduction of new species (Colautti *et al.*, 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intra-specific variation that needs to be preserved for future viability and how much genetic bias is introduced by founder effects and selection pressures applied during ex-situ maintenance is unknown. It remains uncertain whether it is possible to reintroduce species (especially animals) successfully into the wild after generations of ex-situ conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to act to assist ecosystem adaptation to climate change will plausibly leads to ecological, social and economic *damages*. The necessary actions to cope with unavoidable damages generate *adaptation costs*, while *mitigation costs* are associated with actions to tackle undesired future damages. Examples of these costs, based on recent literature, are shown in Table 2-5 in Rodriguez-Labajos (submitted). The timing of the action also has cost implications: increasing costs that result from must be weighed against the risks associated with premature measures (Szlavik and Csete, 2012). In addition to the direct financial costs of action, further costs may appear through trade-offs between services: e.g. afforestation for climate mitigation is costly in terms water provision (Chisholm, 2010). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011), but due to the lower per hectare yields, requires a larger area to be dedicated to cropland.

A comprehensive cost estimate of the effects of climate change on ecosystem service provision is not available. ten Brink *et al.* (2008) report the monetary cost of not meeting the 2010 biodiversity goals in terms of lost value of ecosystem services. Their model incorporates climate change, among other pressures, and concludes that cumulative losses of welfare due to losses in ecosystem service provision could reach an annual amount of 14 trillion Euro (based on values of 2007), in 2050 equivalent to 7% of projected global GDP for that year.

Economic calculations are appropriate when at least one component of the ecosystem services is traded in markets (such as for biofuels; Mishra *et al.*, 2010). If climate regulation services are translated into a tradable item, through carbon markets or payments for avoiding deforestation, then their value can be expressed via market prices (Shaw *et al.*, 2011).

The market price for carbon is volatile, linked to speculation and political agreements on emission reduction. There is a range of estimates from $23/metric ton of carbon to $371, in current 1995 and 2007 dollars respectively (Tol, 2008; Watkiss and Downing, 2008). In the South-African Fynbos region, economic viability of afforestation proved to be highly sensitive to the value of carbon (Chisholm, 2010). The realized prices of the traded carbon have been on

average lower than the figures mentioned above. The proposed global REDD programs, financed by carbon-offset trading, rely on the premises on which market-based payment for ecosystem services (PES) are founded. However, a decade of PES experience demonstrates a clash between market-efficiency criteria and poverty reduction and therefore a risk of regressive wealth redistribution (McAfee, 2012).

Uncertainty about the potential consequences of abrupt changes advises against valuation of ecosystems close to critical thresholds (TEEB, 2009). Similar difficulties can be argued in the presence of irreversible changes, as in the case of irreversible biodiversity losses or damage to cultural services such as World Heritage sites (Viles and Cutler, 2012).

4.4.4. Unintended Consequences of Adaptation and Mitigation Actions in This and Other Sectors

Some issues relevant to this section are also found in 4.2.2 and in Chapter 14.

Several of the alternatives to fossil fuel require extensive use of the land surface. Bio-energy requires land to either be taken from food production or from natural ecosystems. Many renewables require significant land areas. Hydroelectricity usually involves the impoundment of large bodies of water behind dams, leading to flooding of pre-existing ecosystems. Solar energy effectively involves decreasing the albedo of areas of ground surface. Large-scale wind energy involves the location of arrays of turbines across the landscape. As an illustration, the "aggressive mitigation" scenario RPC2.6 relies heavily on both bio-energy and renewables as major components of the energy mix (van Vuuren *et al.*, 2011), so there is clear potential for unintended consequences for terrestrial and inland water systems.

In RCP2.6, although food production remains dominant, the scenario still involves some land use / land-cover change (Box 4-1) in order to facilitate the use of bio-energy. By 2100, bio-energy crops occupy approximately 4 million km^2, approximately 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risk (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive and "natural" areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may pose extinction risks.

RCP2.6 also includes a substantial increase in renewables above current levels of deployment, either as hydropower, solar or wind. Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, e.g., of amphibians (Brandão and Araújo, 2007). Large dams may also result in CH_4 emissions due to decay of flooded vegetation in anaerobic conditions and the subsequent release of CH4 from the water surface and especially from water passing through turbines and spillways (Fearnside, 2005; Lima *et al.*, 2008), so dams may act as sources of greenhouse gas emissions.

Concern is often raised over wind turbines posing a danger to birds and bats, but estimating mortality rates is complex and difficult (Smallwood, 2007). It has been estimated that wind farms in Europe and the USA cause between 0.3 and 0.4 wildlife fatalities per gigawatt-hour (GWh) of electricity, and while nuclear and fossil-fuel power stations are estimated to cause approximately 5.2 fatalities per GWh (Sovacool, 2009), although this quantification has been criticized as having key methodological flaws (Willis *et al.*, 2010b). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins *et al.*, 2012)

Solar energy systems, by design, aim to maximize the absorption of solar energy and hence widespread deployment of photovoltaics (PV) has the potential to exert a positive radiative forcing on climate through decreased surface albedo. In a scenario of widespread deployment of solar PV, such a forcing is estimated to be 30 times smaller than the avoided radiative forcing arising from the use of PV to substitute fossil fuels, so overall PV still exerts a net reduction of climate warming (Nemet, 2009). Nevertheless, at the local scale there are some plausible circumstances in which the decreased surface albedo substantially reduces the effectiveness of PV as a negative climate forcing (Nemet, 2009).

Adaption measures may also result in unintended consequences. Relocation of agricultural areas as a climate change adaptation measure could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation through bio-energy. Deliberate relocation of vulnerable and important species – assisted migration – may also be a potential conservation measure in the context of facilitating adaptation to climate change (Maclachlan *et al.*, 2007). However this may directly conflict with other conservation priorities, for example by actually facilitating the introduction of invasive species (Maclachlan *et al.*, 2007).

Proactive adaptation measures may also have unforeseen consequences politically. Carey *et al.* (2011) argue that improved water management in a glacial lake in the Peruvian Andes in 1985 led to increased tensions over many years and ultimately local civil action against the authorities in 2008. Introduction of a tunnel to reduce the risk of a glacial lake outburst flood facilitated proactive human management of the lake levels, but in the context of changes in the wider political situation, power struggles arose between different stakeholders due to different and conflicting interests. This may provide an example of how attempts by society to exert more direct control over the environment can lead to unintended impacts.

4.5. Emerging Issues and Key Uncertainties

The presence of thresholds in ecosystem response to climate change, and specifically the type of thresholds characterized as “tipping points’, is a growing concern but remains a major source of uncertainty. In general (Field *et al.*, 2007), negative feedbacks currently dominate the climate-ecosystem interaction, but in several areas, such as the boreal ecosystems, positive feedbacks could dominate, even under moderate warming. For most ecological processes, increasing magnitude of warming shifts the balance towards positive rather than negative feedbacks (Field *et al.*, 2007). For positive feedbacks to propagate into ‘runaway’ processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible and immanent ecological process; but the risk is non-negligible and the consequences if it did occur would be severe: thus further research is needed. The issue of biophysical feedbacks between ecosystem state and the climate, over and above the effects mediated through greenhouse gases, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

Uncertainty in predicting the response of ecosystems to climate and other perturbations remains a major impediment to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent complexity of ecosystems, especially where they are coupled to equally-complex social systems. The high number of interactions can lead to cascading effects (Biggs *et al.*, 2011). Some of this uncertainty can be removed by understanding the systems better, but some will remain irreducible because of the failure of predictive models when faced with mathematical bifurcations – a problem that is well-known in climate science. Probabilistic statements about the range of outcomes are possible in this context, but ecosystem science is mostly as yet unable to conduct such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes unequivocally to climate change. More comprehensive monitoring is a key element of the solution.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated carbon dioxide and rising tropospheric ozone on plant productivity - which has critical consequences for the suture sink strength of the biosphere, since they of similar magnitude but opposite sign – are needed as a supplement to the single-factor experiments.

Understanding of the tolerable *rate* of climate change is as important as understanding the tolerable *magnitude.* Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The costs of assisted adaptation ecosystems, biodiversity and ecosystem services to a changing climates is poorly known, as are the costs of failing to do so.

Frequently Asked Questions

FAQ 4.1: How does climate change contribute to species extinction?

Species extinctions are of considerable concern because they represent irreplaceable losses of unique life forms and because species loss has been shown to degrade the functioning of ecosystems in some cases. Most species extinctions in the recent past can be attributed to habitat destruction, invasive species, overexploitation and pollution. Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these current extinctions is the subject of considerable debate. Over the coming century, climate change is foreseen to increase extinction risk because some species will not be able to adapt to new environments, nor move areas where climate becomes suitable. There is consensus that minimizing climate change will help protect species from extinctions. Under the highest rates of projected climate change, observations and models indicate that many species will be unable to move fast enough to track suitable climate or their ranges will shrink considerably. There is concern that this will substantially increase extinction risk for a large fraction of species, especially when combined with other global change pressures such as habitat destruction. We are, however, currently unable to accurately quantify this risk. Under the lowest projected rates and amounts of climate change and with the assistance of effective conservation actions, the large majority of species are foreseen to be able to adapt to the new climates, or respond by moving to higher latitudes or altitudes.

FAQ 4.2: Why does it matter that ecosystems are altered by climate change?

Ecosystems are the machinery that delivers things essential for all people, everywhere in the world – including obvious items like food, clean water and timber, but also less-obvious ones such as control of pests and diseases, regulation of the climate and a life-supporting atmosphere and pollination of flowers. When ecosystems change, their capacity to supply these services changes as well, for better or worse. Humans are directly affected, as are the millions of other species dependent on ecosystems. ”Ecosystem change” includes the species it contains and in what amounts and proportions, how the ecosystem looks (e.g. tall or short, open or dense) and how it works (e.g. whether it is productive or unproductive). Climate change, among other factors, has an effect on all these aspects of ecosystems, as well as on the total area occupied by particular ecosystems and its geographical location. Ecosystem change has knock-on effects on many sectors, including human health through altering where diseases are found, agriculture through grazing supply and pollinators, infrastructure through changing risks of flooding. Although in the long-term not all ecosystem changes are detrimental to all people or all species, rapidly-changing ecosystems will require adaptation, perhaps in excess of their adaptive capacity, by both the people and organisms dependent on them.

FAQ 4.3: What are the non-greenhouse gas effects of rising carbon dioxide?

Some greenhouse gases exert influences on the environment other than their impact on radiative forcing. The concentration of carbon dioxide affects photosynthesis and transpiration in plants, with photosynthesis generally being enhanced under higher CO_2 concentrations while transpiration is generally decreased. The growth of plants and/or the efficiency with which they use water can therefore be increased. The response varies considerably between species. Increased atmospheric CO_2 concentration also increases the acidity of water, with negative consequences for organisms with calcium carbonate shells, which cannot be grown under low pH.

FAQ 4.4: What costs are caused by changes in ecosystem services due to climate change?

Climate change will certainly alter the services provided by in ecosystems, and on balance, for high degrees of change, in an overall negative way. For instance, coral reefs protect the coast against extreme storm events, which are predicted to increase under climate change – but the reefs are at risk due to bleaching induced by temperature rise, as well as due to ocean acidification. This service alone has been valued at several 1000 $/ha per hour. Other costly damages could include a decrease in pollination services due to climate change related asynchrony of flowering time of plants and activity periods of pollinators. This service is worth worth EUR 153 billion per year (a value that nearly doubles if you take into account purchasing power parity of the affected countries)

FAQ 4.5: What are the opportunities for better managing ecosystems under climate change?

Management of ecosystems can help to mitigate climate change . Forests, for example deliver a wide set of services, including climate regulation. Ecosystems can also be managed to increase their ability to cope with climate change. Reducing the many other stresses on ecosystems – such as excessive harvest, habitat fragmentation and pollution is an important strategy. Maintaining biological diversity and near-natural disturbance regimes also helps. We may need to take drastic action such as assisting species to migrate, or protecting them out of the wild until such time as they can be reintroduced.

FAQ 4.6: Can land-use and land-cover changes cause changes in climate?

Land-use change can affect the local climate, and even the global climate. It does so by changing the emission or uptake of greenhouse gases, but also by changing how much solar energy is absorbed by the land surface. Depending on the type of change and where it occurs, the effects can be either warming or cooling. The effects on precipitation are equally variable and context-dependent. At a global scale, the conversion of forests to croplands, pastures and urban areas is currently contributing around a fifth of the overall emissions of the greenhouse gases which are causing climate change.

FAQ 4.7: Will the number of alien species increase due to climate change?

An alien species, also called exotic or non-native species is one that has been introduced to a region outside of its native geographic range as a deliberate or accidental consequence of human activity. They are called invasive when they cause ecological and/or economic damages as well as if they spread fast and produced a high amount of fertile offspring. The number of new species and the abundance of some already established alien species will increase in certain areas, such as polar regions, due to climate change improving conditions for these species, e.g. higher winter temperatures or longer growing seasons. Increased globalization of goods and human transportation and increased global land use changes are both likely to increase the frequency, establishment and damages of alien invasive species throughout the world although management actions to prevent the transfer of alien species (e.g. through treatment of ballast water and wood products and strict quarantine protocols applied to crop and horticultural products and embargos on trade and deliberate introductions of known invaders) are more and more applied. Some invasive plants and insects have already been shown to benefit from climate change and will likely establish and spread into new regions, once they are introduced there. However, other invasive species will suffer from climate change and, as for most of the biodiversity, are expected to decrease in range and population size in some regions. Within just the Family of ants, some highly invasive species are expected to benefit from climate change and increase their potential invasive areas, while some others will likely much recede.

Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favored by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

Cross-Chapter Boxes

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based approaches to adaptation (also termed Ecosystem-based Adaptation, EBA) integrate the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe *et al.*, 2011; Munroe *et al.*, 2011). EBA is implemented through the sustainable management of natural resources, as well as conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls *et al.*, 2009). The CBD COP 10 Decision X/33 on Climate Change and Biodiversity states further that effective EBA also “takes into account the multiple social, economic and cultural co-benefits for local communities”.

The potential for EBA is increasingly being realized (e.g., Munroe *et al.*, 2011), offering opportunities that integrate with or even substitute for the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees, may adversely affect biodiversity, resulting in maladaptation due to damage to ecosystem regulating services (Campbell *et al.*, 2009, Munroe *et al.*, 2011). There is some evidence that

the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). Well-integrated EBA is also more cost effective and sustainable than non-integrated physical engineering approaches, and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. EBA also offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes.

EBA provides opportunities particularly in developing countries where economies depend more directly on the provision of ecosystem services (Vignola *et al.*, 2009), to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang *et al.*,). In these settings, ecosystem-based adaptation projects may be readily developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan *et al.*, 2012, Midgley *et al.*, 2012; Roberts *et al.*, 2012)

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Midgley *et al.*, 2012, Opperman *et al.*, 2009).
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands and deltas) to provide effective measure against storm-surges, saline intrusion and coastal erosion;
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding;
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques;
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

It is important to assess the appropriate and effective application of EBA as a developing concept through learning from work underway, and to build understanding of the social and physical conditions that may limit its effectiveness. Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.]

CC-EA References

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Box CC-RF. Impact of Climate-Change on Freshwater Ecosystems due to Altered River Flow Regimes

[Petra Döll (Germany), Stuart E. Bunn (Australia)]

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff *et al.*, 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e. changes to the frequency, magnitude, duration and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino *et al.*, 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario, 15% of the global land area may suffer, by the 2050s, from a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, like in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased run-off during winter months (Renofalt *et al.*, 2010).

[INSERT FIGURE RF-1 HERE
Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.]

Because biota are often adapted to a certain level of river flow variability, the larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke *et al.*, 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah *et al.*, 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5-7% of the global land area, mainly in semi-arid areas (Döll and Müller Schmied, 2012; see Chapter 3, Table 3-2).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme *et al.*, 2010). Eco-regions containing over 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary

phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme *et al.*, 2010).

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (chapter 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase, when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C and 3.8°, respectively (van Vliet *et al.*, 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet *et al.*, 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

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Box CC-VW. Active Role of Vegetation in Altering Water Flows Under Climate Change

[Richard Betts (UK), Dieter Gerten (Germany), Petra Döll (Germany)]

Terrestrial vegetation dynamics, carbon and water cycles are closely coupled, for example by the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis, and by feedbacks of land cover and land use change on water cycling.Numerous experimental studies have demonstrated that elevated atmospheric CO_2 concentration leads to reduced opening of stomatal apertures, associated with a decrease in leaf-level transpiration (de Boer *et al.*, 2011; Reddy *et al.*, 2011). This physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (iWUE) of plants, as less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) corroborate this finding, suggesting an increase in iWUE of mature trees by 20.5% between the 1970s and 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011). However, the physiological CO_2 effect is accompanied by structural changes to C3 plants (including all tree species), i.e. increased biomass production, spatial encroachment and, thus, higher transpiration, as confirmed by Free Air CO_2 Enrichment (FACE) techniques (Leakey *et al.*, 2009).

There are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.*, (2006) which suggested that physiological CO_2effects (lower transpiration) contributed to a supposed global increase in runoff seen in reconstructions by (Labat *et al.*, 2004). However, a more recent dataset (Dai *et al.*, 2009) showed different runoff trends in some areas. Detection of ecosystem influences on terrestrial water flows, hence, critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012).

A key influence on the significance of increased iWUE for large-scale transpiration is whether overall leaf area of

primary vegetation has remained approximately constant (Gedney *et al.*, 2006) or has increased in some regions due to structural CO_2effects (as assumed in models by Piao *et al.*, 2007; Gerten *et al.*, 2008). While field-based results vary considerably between sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 200 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009), which is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 rise (McMahon *et al.*, 2010). The net impact of CO_2 on global-scale transpiration and runoff therefore remains poorly constrained.

Moreover, model results differ in terms of the importance of CO_2 effects for historical runoff relative to other drivers such as climate, land use change and irrigation water withdrawal. Other than Gedney *et al.*, (2006), Piao *et al.*, (2007) and Gerten *et al.*, (2008) found that CO_2 effects on global runoff were small relative to effects of precipitation, and that land use change (which often acts to decrease evapotranspiration and to increase runoff) was of second-most importance, as also supported by Sterling *et al.*, (2012) data and model analysis. By contrast, using a shorter time period and a smaller selection of river basins, Alkama *et al.*, 2011(2011) suggested that global effects of land use change on runoff have been negligible. Oliveira *et al.*, 2011(2011) furthermore point to the importance of changes in incident solar radiation and the mediating role of vegetation; their global simulations demonstrate, for example, that a higher diffuse radiation fraction during 1960–1990 increased evapotranspiration in the tropics by 3% due to increased photosynthesis from shaded leaves. Since the anthropogenic component of the precipitation and temperature contributions(i.e. of the radiative CO_2 effect) to runoff trends is not yet established, a full attribution of anthropogenic emissions of CO_2 (and other greenhouse gases)is still missing.

Analogously, there is uncertainty about how vegetation responses to future increases in CO_2 will modulate effects of climate change on the terrestrial water balance.21st-century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when CO_2-induced increases in iWUE are included in addition to climate change (Betts *et al.*, 2007; Murray *et al.*, 2012), potentially reducing an increase in water stress due to rising population or climate change (Wiltshire *et al.*, submitted) – although other models project a smaller response (Cao *et al.*, 2009). Direct effects of CO_2 on plants have been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012), depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the climate are accounted for. The model analysis by Alkama *et al.*, (2010) suggests that although the physiological CO_2 effect will be the second-most important factor for 21st-centuryglobal runoff and although both physiological and structural effects will amplify compared to historic conditions, runoff changes will still primarily follow the projected climatic changes. Using a large ensemble of climate change projections, Konzmann *et al.*, (2013) put hydrological changes into an agricultural perspective and suggest that direct CO_2 effects on crops reduce their irrigation requirements (Fig. CC-VW-1). Thus, adverse climate change impacts on crop yields might be partly buffered as iWUE improves (Fader *et al.*, 2010), but only if proper management abates limitation of plant growth by nutrient availability or other factors. Lower transpiration under rising CO_2 may also affect future regional climate change itself (Boucher *et al.*, 2009) and may enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008).

Application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to changes in different climatic variables mediated by vegetation,with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). In a warmer climate with increased atmospheric CO_2 concentration, iWUE of plants increases and leaf area may either increase or decrease, and even though precipitation may slightly decrease, groundwater recharge may increase as a net effect of these interactions (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a location in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Future anthropogenic and climate-driven land cover and land use changes will also affect regional evapotranspiration, surface and subsurface water flows, with the direction and magnitude of these changes

depending on the direction and intensity of the changes in vegetation coverage,as shown e.g. for a river basin in Iowa (Schilling *et al.*, 2008) or for the Elbe river basin (Conradt *et al.*, 2012).Removal of vegetation acting as source of atmospheric moisture can change regional water cycling and decrease potential crop yields by up to 17%in regions otherwise receiving this moisture in the form of precipitation (Bagley *et al.*, 2012).Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the climate system such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011) in that e.g. vegetation structure and composition can dynamically adapt to changing climatic and hydrologic conditions (Gerten *et al.*, 2007), it remains a challenge to disentangle the effects of future land cover changes on the water cycle.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).]

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Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use

(kWhr/m^3) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.,* 2008, Bazilian *et al.,* 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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Table 4-1: Biome shifts from 1700 to the present from published field research that examined trends over periods > 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.* (2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). Biomes (and abbreviations), from poles to equator: tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate shrubland (TS), tropical grassland (RG), tropical woodland (RW). Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. * rate significant at $P \leq 0.05$).

	Location	Reference	Plots	Time Period	Shift type	Retracting biome	Expanding biome	Temp. change (°C century^{-1})	Precip. change (century^{-1})
1.	Alaska Range, Alaska, USA	Lloyd and Fastie, 2003	18	1800-2000	L	UA	BC	1.1*	0.03
2.	Baltic Coast, Sweden	Walther *et al.*, 2005	7	1944-2003	L	TC	TB	0.6*	0.08
3.	Becca di Viou, Italy	Leonelli *et al.*, 2011	1	1700-2008	E	UA	BC	0.9*	-0.06
4.	Garibaldi, British Columbia, Canada	Brink, 1959	1	1860-1959	E	UA	BC	0.7*	0.16*
5.	Goulet Sector, Québec, Canada	Payette and Filion, 1985	2	1880-1980	E	UA	BC	1.4*	0.19*
6.	Green Mountains, Vermont, USA	Beckage *et al.*, 2008	33	1962-2005	E	BC	TB	1.6*	0.06
7.	Jasper, Alberta, Canada	Luckman and Kavanagh, 2000	1	1700-1994	E	UA	BC	0.6	0.21*
8.	Kenai Mountains, Alaska, USA	Dial *et al.*, 2007	3	1951-1996	E	UA	BC	0.7	0.06
9.	Kluane Range, Yukon, Canada	Danby and Hik, 2007	2	1800-2000	E	UA	BC	0.7	0.05
10.	Low Peninsula, Québec, Canada	Payette and Filion, 1985	1	1750-1980	N	-	-	1.4*	0.19*
11.	Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald, 1995	13	1700-1990	N	-	-	1.4*	0.03
12.	Montseny Mountains, Catalonia, Spain	Peñuelas and Boada, 2003	50	1945-2001	E	UA	TB	1.2*	-0.03
13.	Napaktok Bay, Labrador, Canada	Payette, 2007	2	1750-2000	L	UA	BC	1.1*	0.05
14.	Noatak, Alaska, USA	Suarez *et al.*, 1999	18	1700-1990	L	UA	BC	0.6	0.19*

	Location	Reference	Plots	Time Period	Shift type	Retracting biome	Expanding biome	Temp. change (°C century^{-1})	Precip. change (century^{-1})
15.	Putorana Mountains, Russia	Kirdyanov *et al.*, 2012	10	1500-2000	E	UA	BC	0.3	0.10
16.	Rahu Saddle, New Zealand	Cullen *et al.*, 2001	7	1700-2000	N	-	-	0.6*	0.03
17.	Rai-Iz, Urals, Russia	Devi *et al.*, 2008	144	1700-2002	E	UA	BC	0.3	0.35*
18.	Sahel, Sudan, Guinea zones; Senegal	Gonzalez, 2001	135	1945-1993	L	RW	RG	0.4*	-0.48*
19.	Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez *et al.*, 2012	14	1960-2000	L	RW	RG	-0.01*-to 0.8*	-0.31*-to 0.09
20.	Scandes, Sweden	Kullman and Öberg, 2009	123	1915-2007	E	UA	BC	0.8*	0.25*
21.	Sierra Nevada, California, USA	Millar *et al.*, 2004	10	1880-2002	E	UA	TC	-0.1	0.21*
22.	South Island, New Zealand	Wardle and Coleman, 1992	22	1980-1990	E	TS	TB	0.6*	0.03
23.	Yambarran, Northern Territory, Australia	Sharp and Bowman, 2004	33	1948-2000	N	-	-	-0.06	0.35*

Table 4-2: Summary of drivers and outcomes of land use / cover scenarios associated with Representative Concentration Pathways (Hurtt et al., 2011).

RCP	Key assumptions / drivers	Land use / cover outcomes
8.5-MESSAGE	No climate change mitigation actions; radiative forcing still rising at 2100 Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100) Yield improvements and intensification assumed to account for most of production increases	**Increase in cultivated land by about 305 million ha from 2000 to 2100** **Forest cover declines by 450 million ha from 2000 to 2100** **Arable land use in developed countries slightly decreased - all of the net increases occur in developing countries.**
6.0-AIM	Mitigation actions taken late in the century to stabilize radiative forcing at 6 Wm^{-2} after 2100 Population growth and economic growth Increasing food demand drives cropland expansion	**Urban land-use increases** **Cropland area expands** **Grassland area declines** **Total forested area extent remains constant**
4.5-GCM	Mitigation stabilizes radiative forcing at 4.5 Wm–2 before 2100 Assumes that global GHG emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions charged an equal penalty price, so reductions in land-use change carbon emissions available as mitigation Food demand met through crop yield improvements, dietary shifts, production efficiency and international trade.	**Preservation of large stocks of terrestrial carbon in forests** **Overall expansion in forested area** **Agricultural land declines slightly due to afforestation,**
2.6-IMAGE	Overall trends in land use and land cover mainly determined by demand, trade and production of agricultural products and bio-energy	**Much agriculture relocates from high income to low income regions** **Increase in bio-energy production, new area for bioenergy crops near current agricultural areas.**

Table References Chapter 4 SOD

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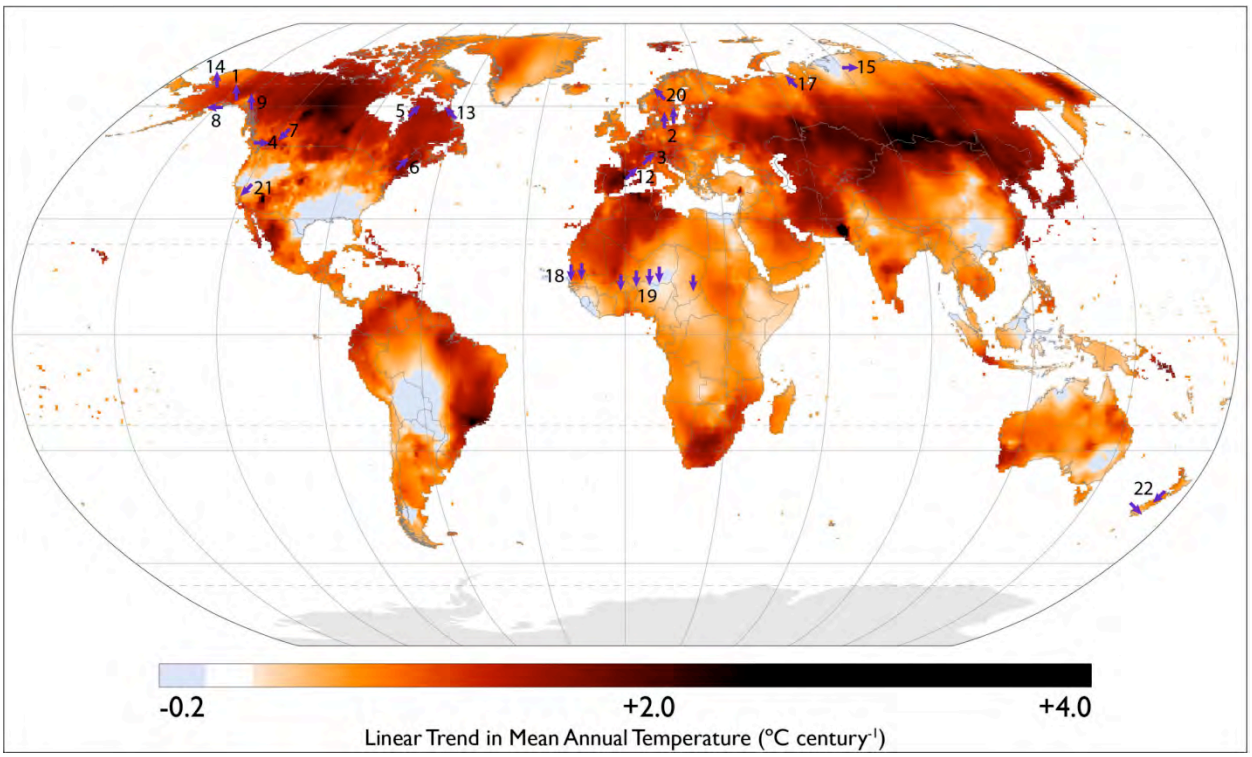

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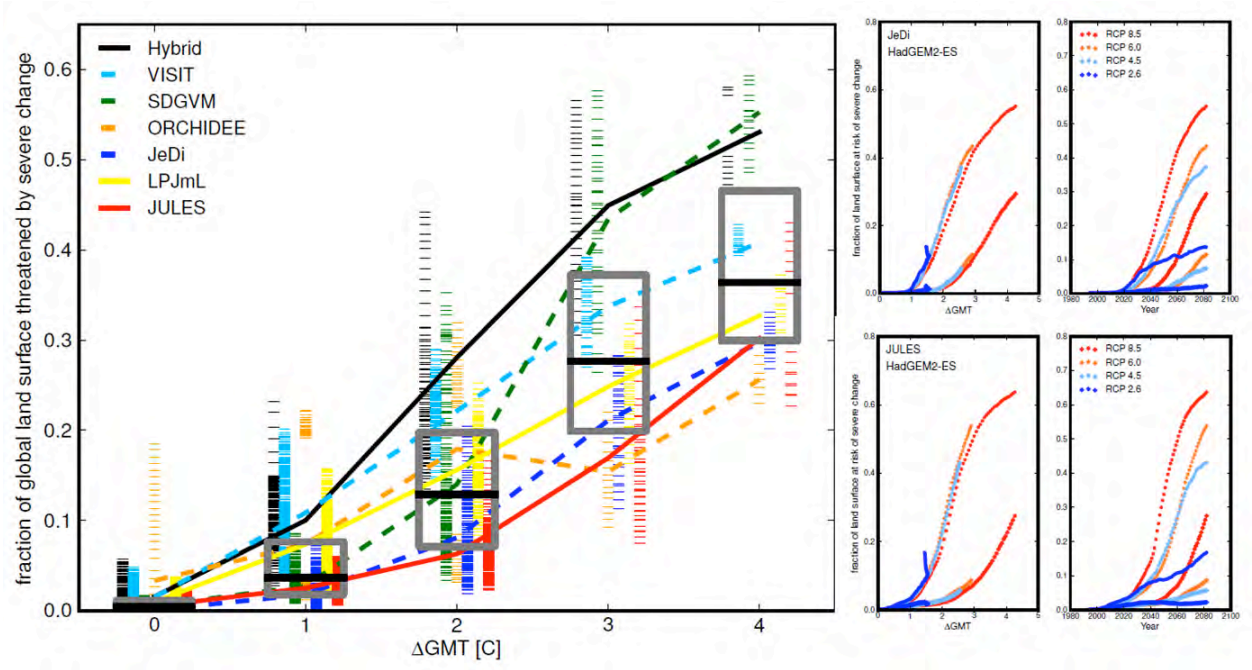

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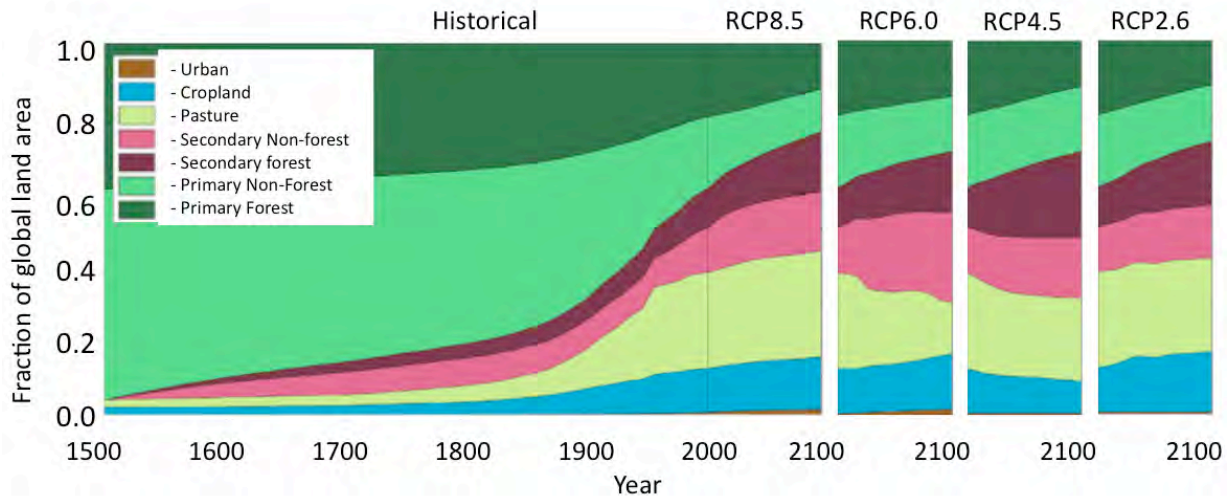

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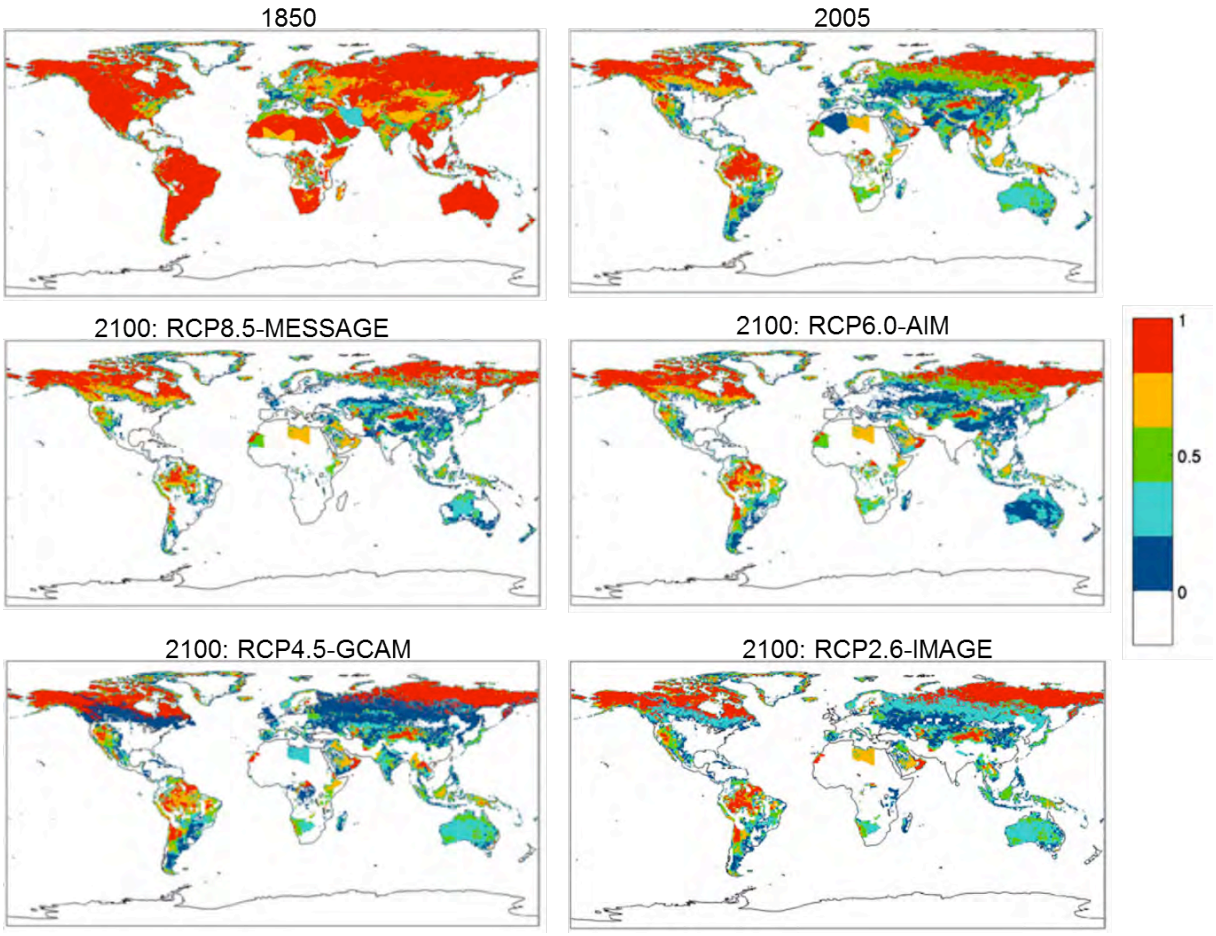

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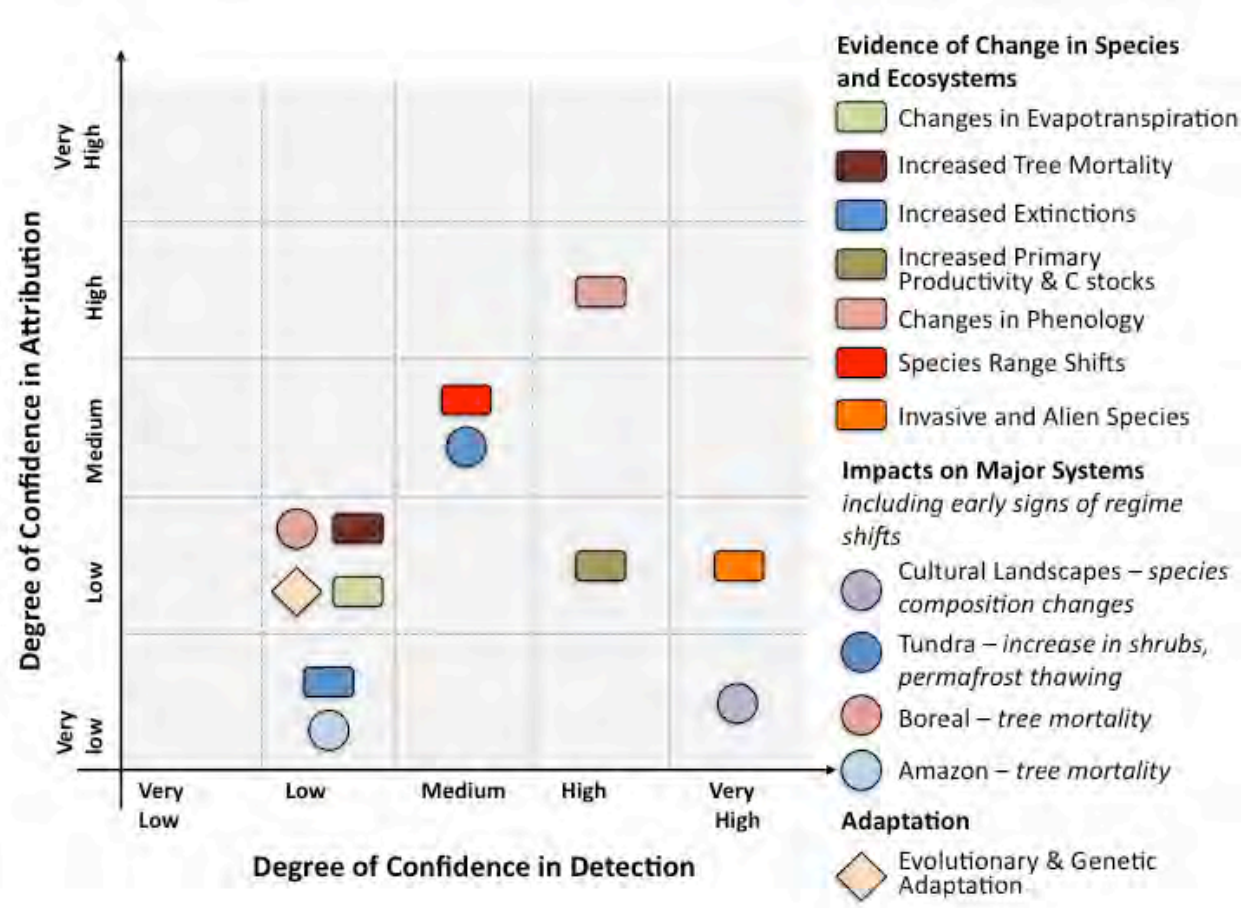


Figure 4-5: Confidence in Detection and Attribution of observed responses of terrestrial ecosystems to climate change.

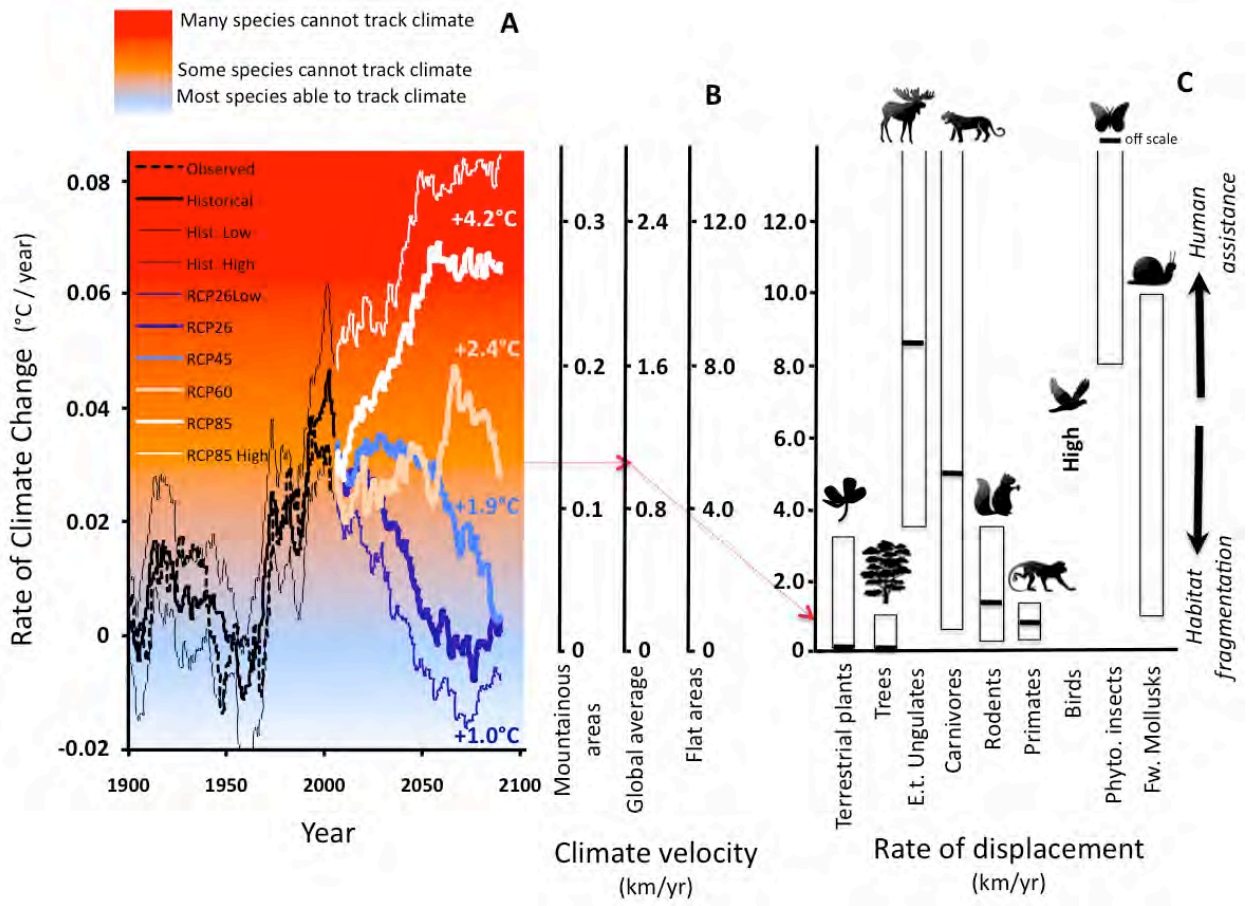


Figure 4-6: Rate of climate change, climate velocity and rate of displacement

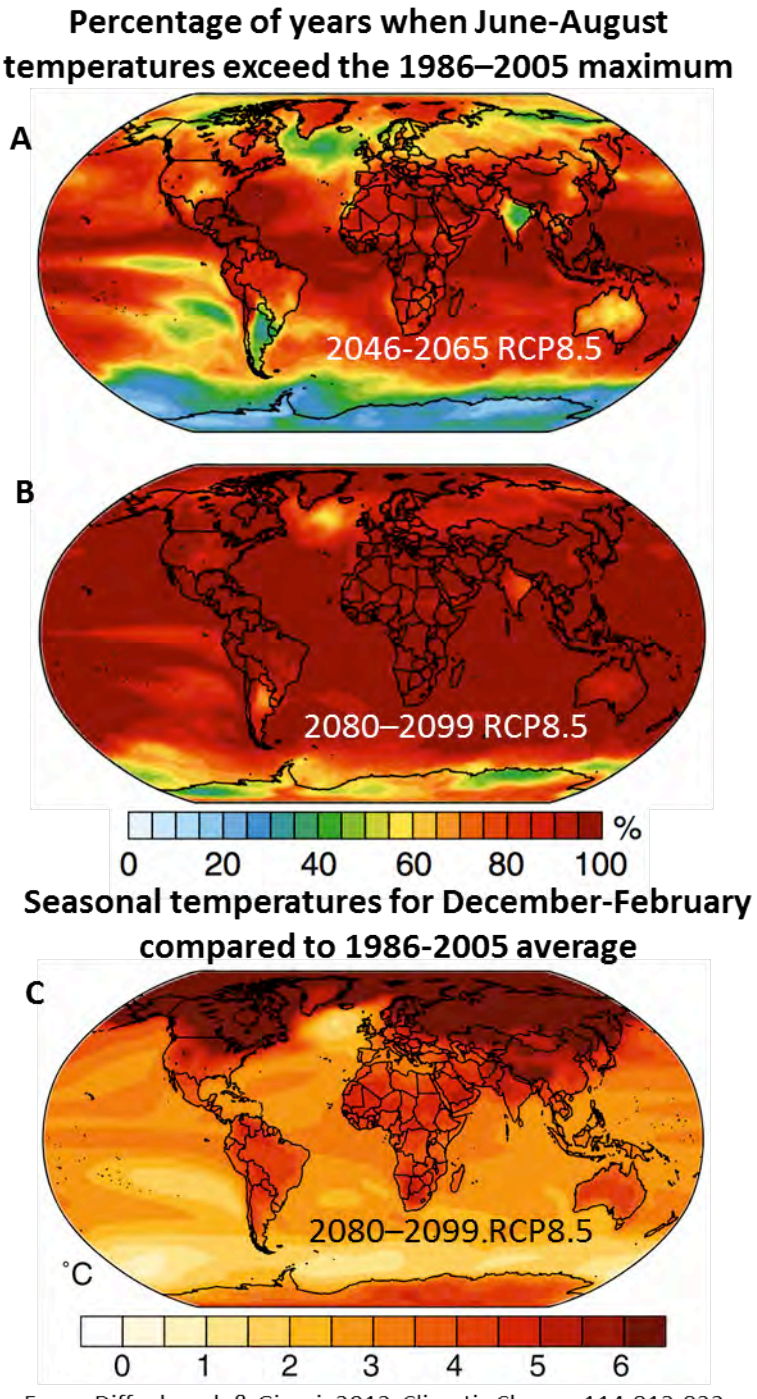
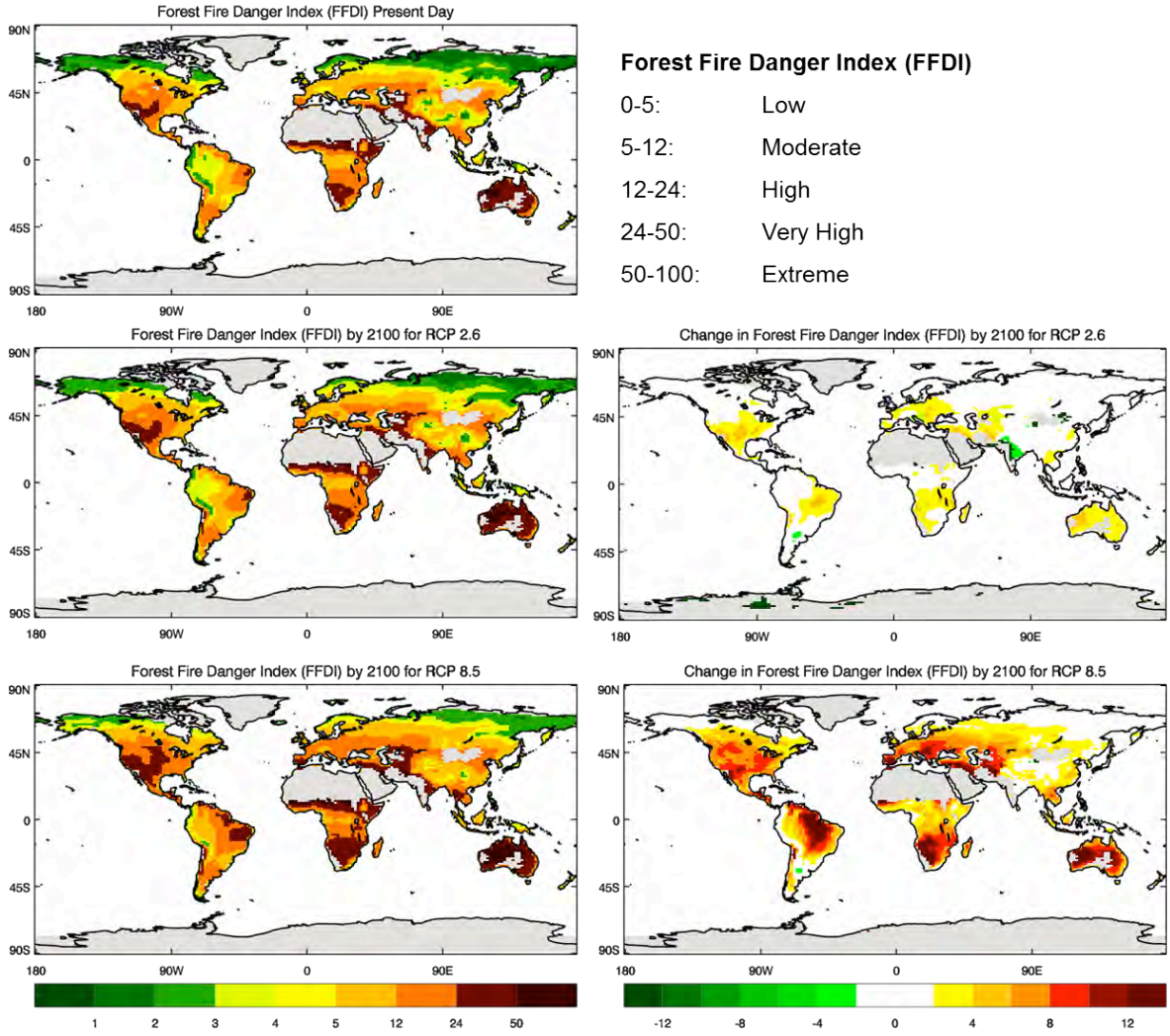


Figure 4-7: Vulnerability of terrestrial biomes to future climate change.



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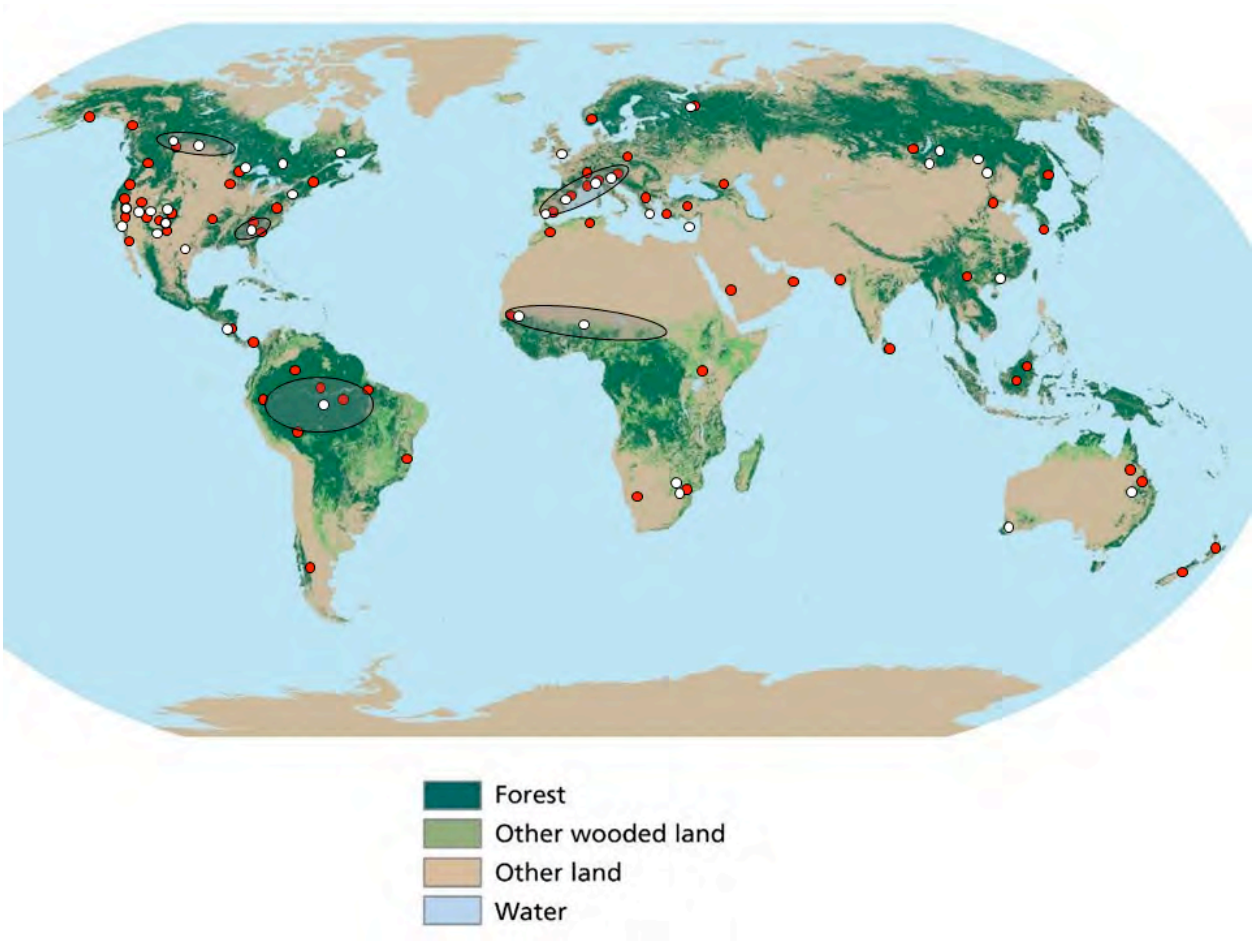

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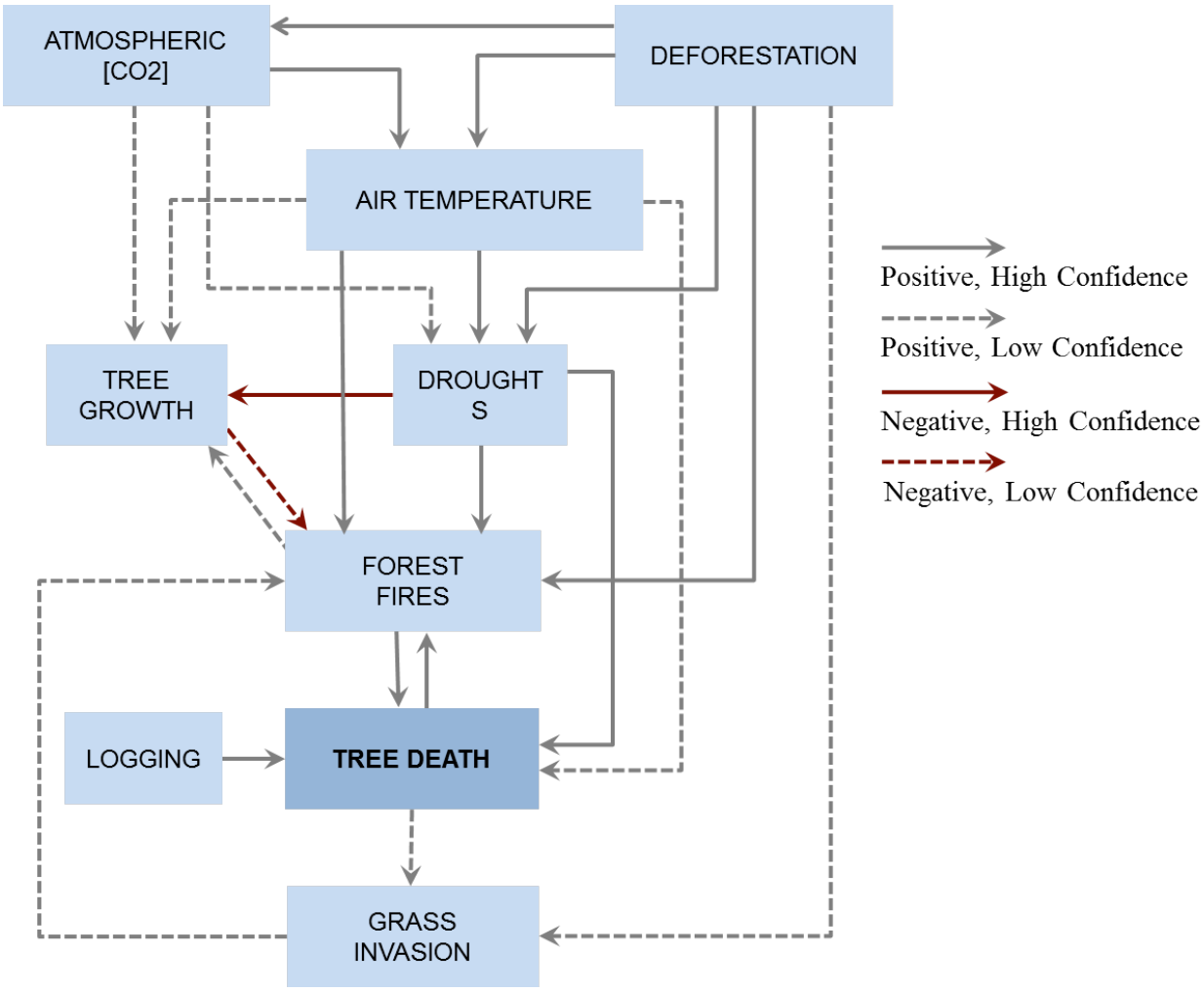

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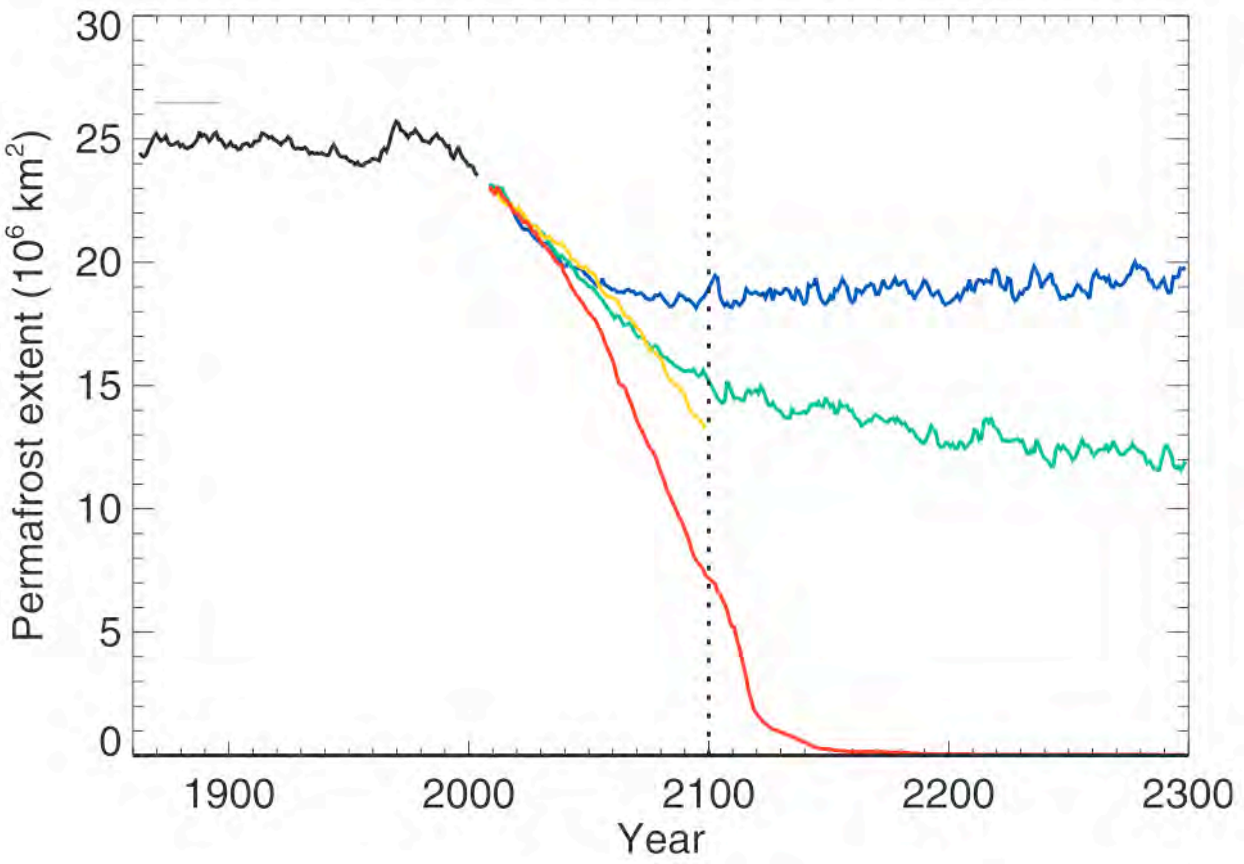

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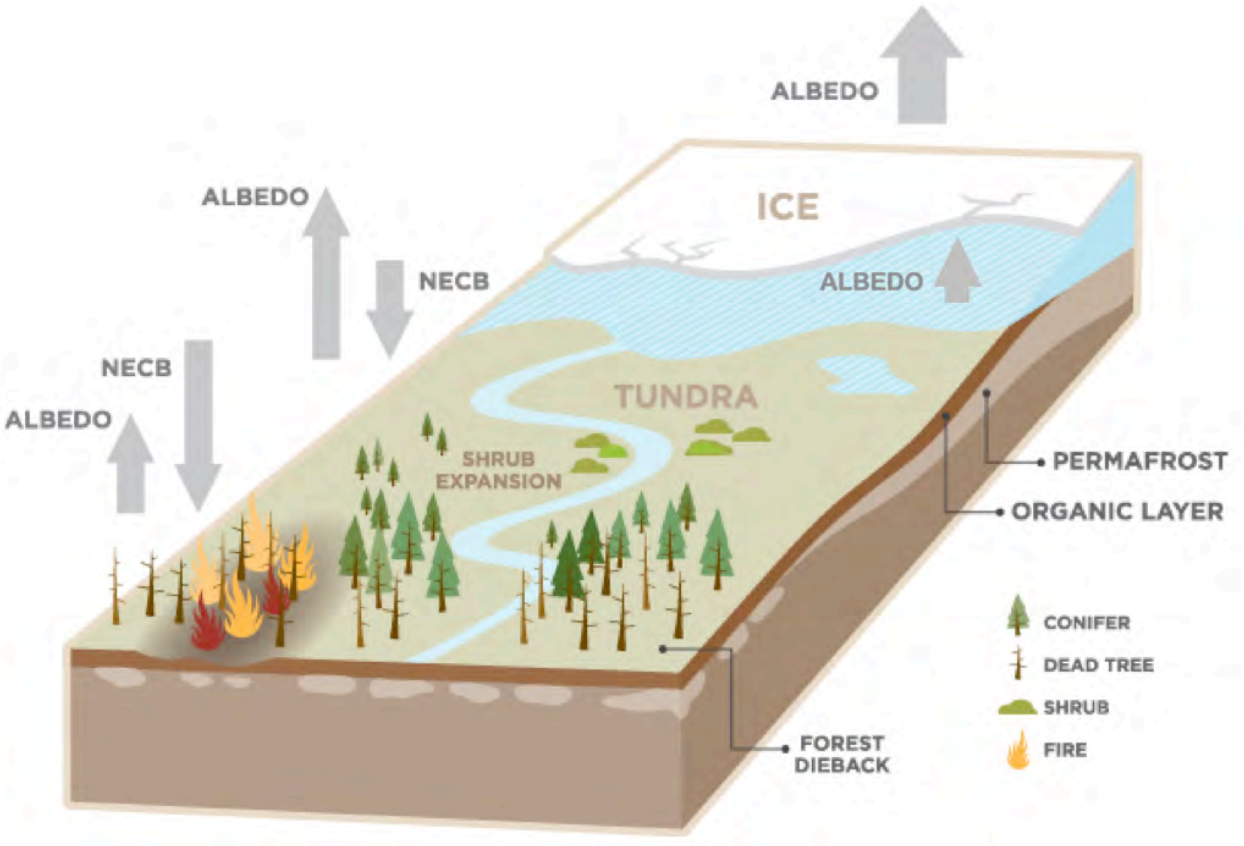

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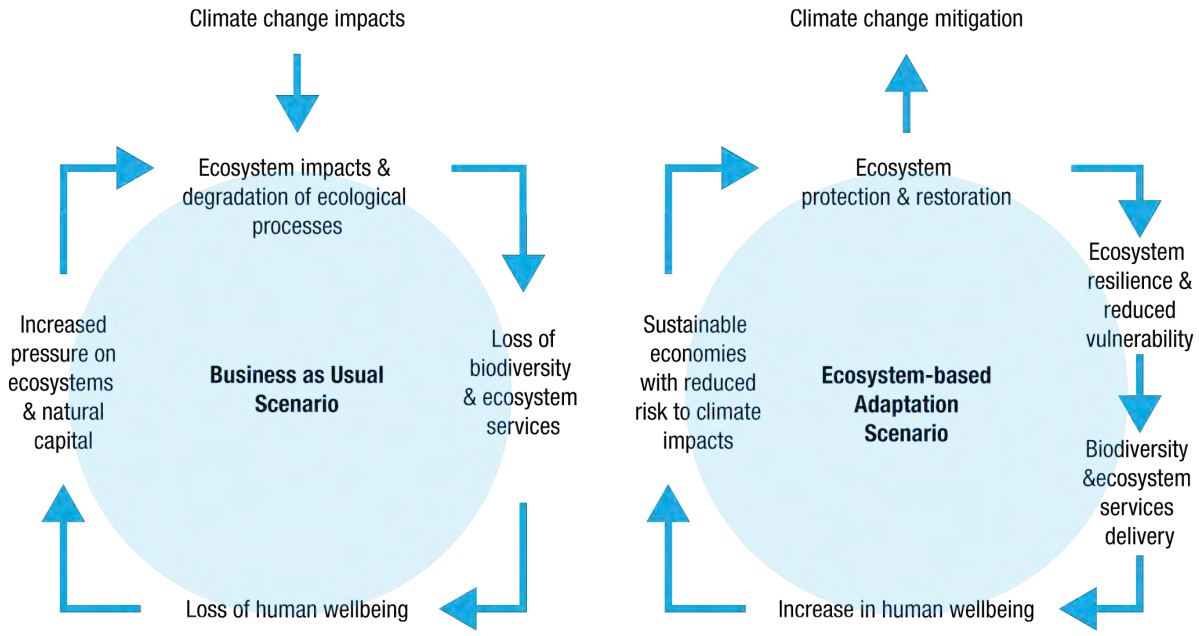


Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.

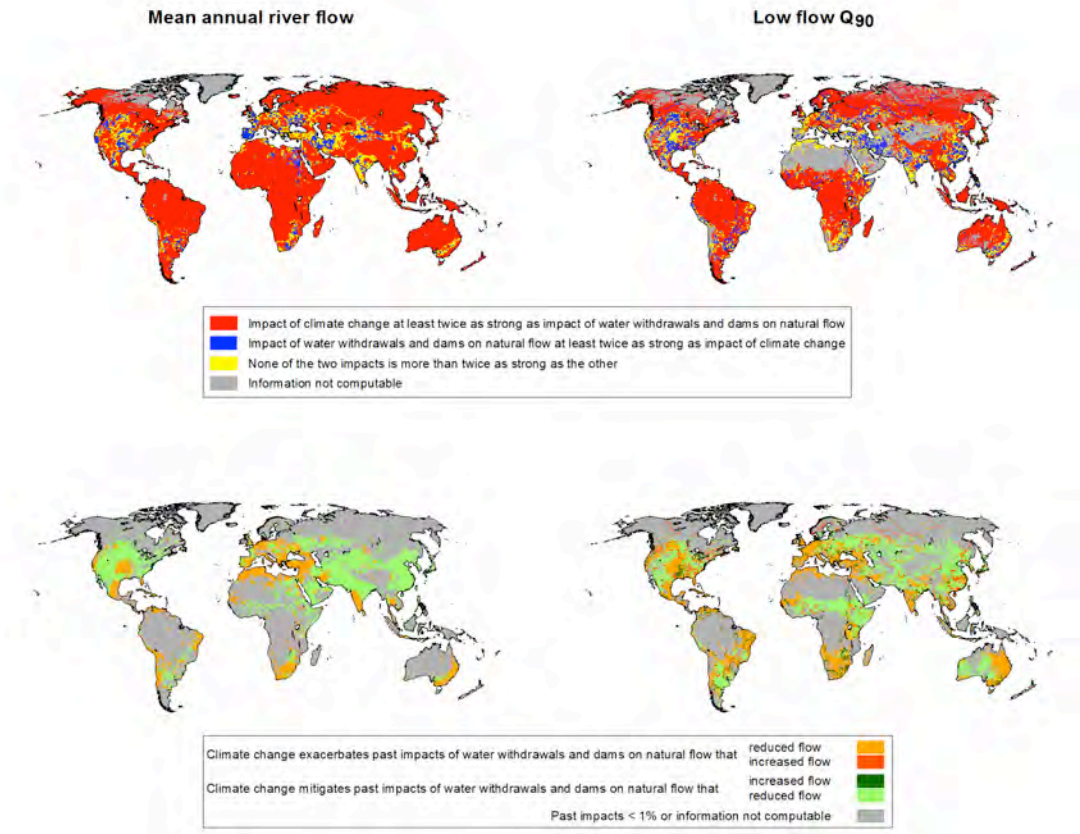


Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.

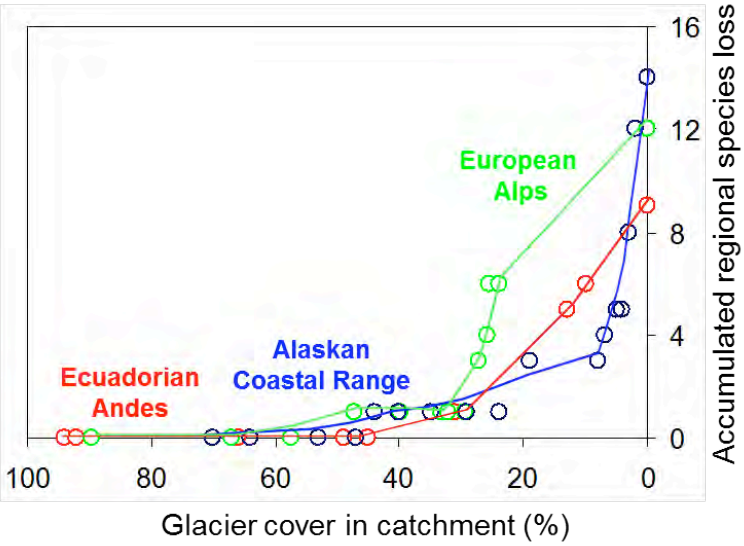
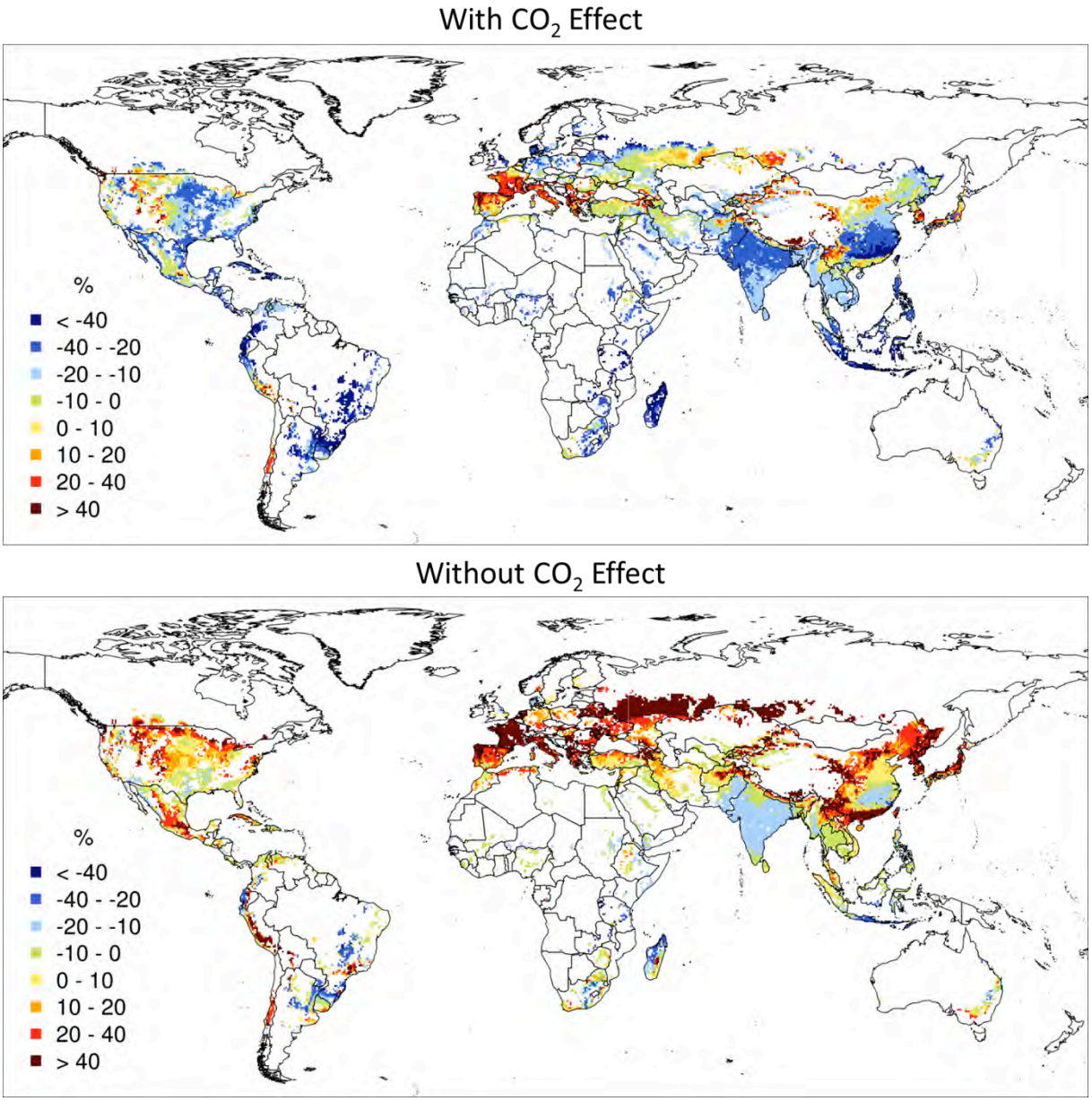


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.



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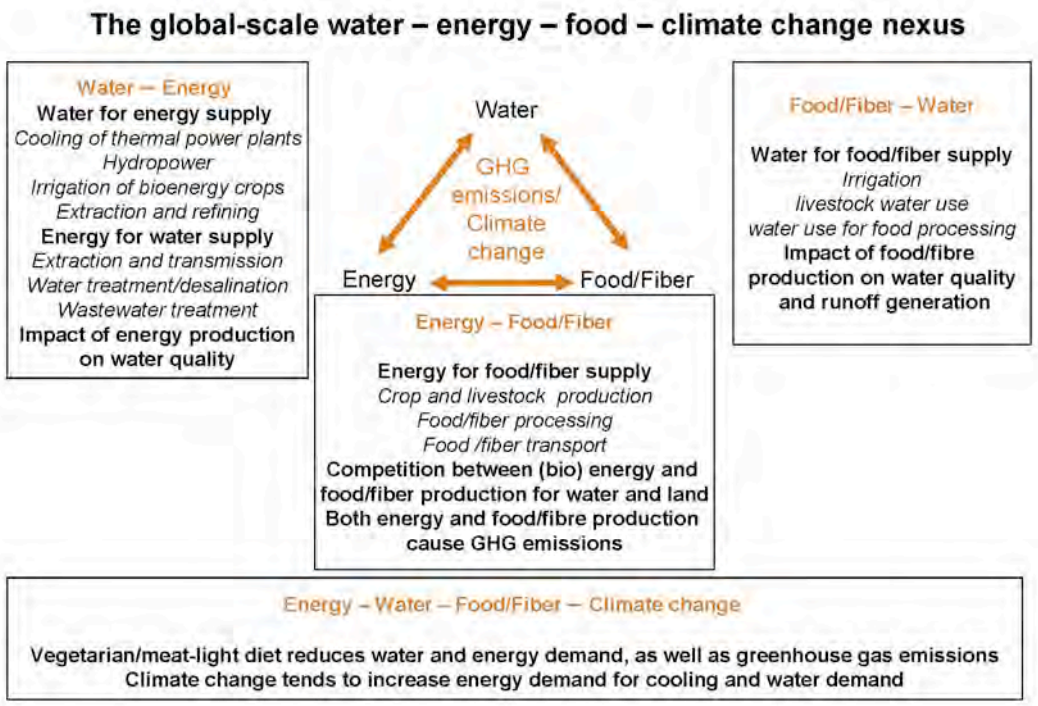

Figure WE-1: The water-energy-food nexus as related to climate change.

Chapter 5. Coastal Systems and Low-Lying Areas

Coordinating Lead Authors
Poh Poh Wong (Singapore), Iñigo J. Losada (Spain)

Lead Authors
Jean-Pierre Gattuso (France), Jochen Hinkel (Germany), Abdellatif Khattabi (Morocco), Kathleen McInnes (Australia), Yoshiki Saito (Japan), Asbury Sallenger (USA)

Contributing Authors
So-Min Cheong (Republic of Korea), Kirstin Dow (USA), Carlos Duarte (Spain), Kris Ebi (USA), Lucy Faulkner (UK), Masahiko Isobe (Japan), Jack Middelburg (Netherlands), Susanne Moser (USA), Mark Pelling (UK), Edmund Penning-Rowsell (UK), Sybil Seitzinger (Sweden), Marcel Stive (Netherlands), Richard Tol (Netherlands), Athanasios Vafeidis (Greece)

Review Editors
Robert Nicholls (UK), Filipe Santos (Portugal)

Volunteer Chapter Scientist
Sara Amez (Spain)

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CC-CR. Coral Reefs
CC-OA. Ocean Acidification
CC-TC. Case Study Building Long Term Resilience from Tropical Cyclone Disasters

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Executive Summary

Coastal systems and low-lying areas will increasingly experience adverse impacts associated with submergence and extreme sea level flooding due to relative sea level rise (*high confidence*). Large spatial variations in the projected sea level rise, together with local factors such as subsidence suggests that relative sea level rise can be considerably larger than projected GMSL and therefore is an important consideration in impact assessments (*very high confidence*) [5.3.1]. Changes in storms and associated storm surges may further contribute to changes in sea level extremes but the small number of regional storm surge studies, limited spatial coverage and different modelling approaches used means that there is *low confidence* in projections of storm surge [5.3.3.2].

Acidification and warming of coastal waters will continue with significant consequences for coastal ecosystems (***high confidence***). The increase in acidity will be higher in areas where eutrophication is an issue with negative consequences for many calcifying organisms (*high confidence*) [5.4.2.2, 5.4.2.4]. The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*) [5.4.2.4, Box CC-OA]. Warming will cause a decline of vegetated coastal habitats across the temperate zone [5.4.2.3]. Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*). The decline of seagrass and kelp habitats will affect food webs, biodiversity and biogeochemical cycling in these ecosystems (*very high confidence)*. In the absence of adaptation, beaches, sand dunes and cliffs currently eroding will continue to do so under increasing sea levels (*high confidence*) [5.4.2.1.-5.4.2.2.]. Increased human-induced drivers have been the primary drivers of change in coastal aquifers, lagoons, estuaries, deltas and wetlands (*very high confidence*). Climate-induced drivers will exacerbate currently existing problems in these natural systems (*very high confidence*) [5.4.2.3-5.4.2.7].

The population and assets exposed to coastal risk as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, urbanization and coast-ward migration of people (*high confidence*). Under medium population projections, the population exposed to the 1 in 100 year coastal flood is expected to increase from 271 million in 2010 to 345 million in 2050 due to socio-economic development only [5.4.3.1]. This increase in coastal population is expected to further exacerbate human pressures on coastal systems resulting from excess nutrient input, reduced run-off and sediment delivery (*high confidence*) [5.3.4.3, 5.3.4.4, 5.3.4.5, 5.3.4.6].

The costs of inaction are larger than the sum of adaptation and residual damage costs for the 21st century and at the global scale (*high agreement*). Without adaptation, hundreds of million people will be affected by coastal flooding and be displaced due to land loss through submergence and erosion by 2100; the majority of these affected are from East, Southeast and South Asia (*high confidence*). [5.4.3.1]. Even with very extreme mean sea-level rise of 1.3m by 2100, protection is considered economically rational for most developed coastlines in most countries (*high agreement*) [5.5.3]. Under medium socio-economic development assumption, the expected direct global annual cost of coastal flooding (adaptation and residual damage costs) may reach US$300 billion per year in 2100 without adaptation and US$90 billion per year with adaptation under a 1.26 m sea-level rise scenario [5.5.3]

The impacts of climate change on coasts and the required level of adaptation vary strongly between regions and countries (*high confidence*). While developed countries are expected to be able to adapt to even high levels of sea-level rise, small island states and some low-lying developing countries are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of GDP (*high agreement*) [5.5.3]. Developing countries and small island states within the tropics relying on coastal tourism, are impacted not only directly by future sea-level rise and associated extremes but also by the impacts of coral bleaching and ocean acidification and reductions in tourist flows from other-regions **(***very high confidence*). [5.4.3.4]

Since AR4, the analysis and implementation of coastal adaptation has progressed significantly but much more effort is needed for a transition towards climate resilient and sustainable coasts (*very high confidence*). The analysis of adaptation has progressed towards novel approaches such as robust decision making and adaptation pathways that recognize that the deep uncertainty in projections of drivers does not have to be a barrier to adaptation (*high confidence*) [5.5.2.2]. Adaptation analysis and implementation have also progressed towards considering the institutional context and governance of adaptation, albeit many governance challenges related to vertical and horizontal policy integration, political will and power relations remain (*very high confidence*) [5.5.2.3, 5.5.2.4]. Many countries, sates/provinces, cities and communities are now carrying out adaptation activities including the mainstreaming of coastal adaptation into relevant strategies and management plans (*very high confidence*) [5.5.4].

5.1. Introduction

This chapter presents an updated picture of the impacts, vulnerability and adaptation of coastal systems and low-lying areas to climate change, with emphasis on sea-level rise. Unlike the coastal chapter in the previous assessment

(AR4), some materials pertinent to the oceans are not covered in this chapter but in two new ocean chapters (Chapters 6 and 30).

The topics covered in this chapter follow the outline for sectoral chapters approved by the IPCC. An Executive Summary summarizes the key messages with a line of sight to the supporting sections in the chapter.

This chapter comprises six sections with this first section dealing with progress in knowledge from AR4 to AR5 scope of chapter and new developments. Section 2 defines the coastal systems and climate and non-climate drivers. The coastal systems include both natural systems and human systems and this division is generally followed throughout the chapter. The climate and non-climate drivers are assessed in section 3, followed by the impacts, vulnerabilities and risks in section 4. Section 5 deals with adaptation and managing risks. Information gaps, data gaps and research needs are assessed in section 6. There are 8 boxes on specific topics or examples, including 3 cross-chapter boxes, distributed within the chapter.

In the AR4, the coasts chapter assessed the impact of climate change and global sea-level rise up to 0.6 m to 2100 The coastal systems were deemed be affected mainly by higher sea level, increasing temperature, changes in precipitation, larger storm surges and reduction in ocean pH. Human activities had continued to increase their pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on the coastal resources. Regionwise, South, Southeast and East Asia, Africa and small islands were identified most vulnerable. The AR4 chapter offered a range of adaptation measures, many under the ICZM (integrated coastal zone management) framework that could be carried out in the developed and developing countries, but recognized that the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience of coastal communities were discussed. The unavoidability of sea level rise in the long term, even with stringent mitigation was noted, and adaptation would become an urgent issue.

A number of key issues related to the coasts have arisen since the AR4. There is now better understanding of the natural systems, their ecosystem functions, their services and benefits to humanity and how they can be affected by climate change. Their linkages landward to the watersheds and seaward to the seas and oceans need to be considered for a more integrated assessment of climate change impacts. GMSL are projected to be 0.46 to 0.96 cm by 2100 although regional variations in sea level rise may see values vary by up to 20% of GMSL for most countries and as much as 50% for some (WG1 Chapter 13). This may have serious implications for coastal cities, deltas and low-lying states. While higher rates of coastal erosion are generally expected under rising sea levels, the complex inter-relationships between the geomorphological and ecological attributes of the coastal system and the relevant climate and oceanic processes need to be better established at regional and local scales.

Also of concern is ocean acidification and potential impacts of reduced calcification in shellfish and impacts on commercial aquaculture (Barton *et al.*, 2012). Together with warming, acidification also causes coral reefs to lose their structural stability with negative implications for reef communities and shore protection (Sheppard *et al.*, 2005; Manzello *et al.*, 2008; see also Box CC-OA). A significant number of new findings regarding the impacts of climate change on human settlements, key coastal systems such as rocky coasts, beaches, estuaries, deltas, salt marshes, mangroves, coral reefs and submerged vegetation have become available since the AR4 and are reviewed in this chapter. However, uncertainties regarding projections of potential impacts on coastal systems remain high.

This chapter also provides advances in both vulnerability assessments and the identification of potential adaptation actions, costs, benefits and tradeoffs. A larger number of new studies estimate the cost of inaction versus potential adaptation. Coastal adaptation has become more acceptable and a wider range of approaches and frameworks such as integrated coastal management, ecosystem-based adaptation, community-based adaptation and disaster risk reduction and management are being used.

Climate change will interact differently with the variety of human activities and other drivers of change along coastlines of developed and developing countries. For coastlines of developed countries, changes in weather and climate extremes and sea-level rise may impact for example, demand for housing, recreational facilities and construction of renewable energy infrastructure at the coast (Hadley, 2009). On coasts of developing countries,

weather and climate extremes put an additional risk to many of the fastest-growing coastal urban areas, such as in Bangladesh and China (McGranahan *et al.,* 2007; Smith 2011).

5.2. Coastal Systems

Coastal systems and low-lying areas, also referred to as simply coasts in this assessment are areas near to mean sea level. Generally, there is no single definition for the coasts and the coastal zone/area where the latter has an emphasis on area or extent. In relation to exposure to potential sea-level rise, the LECZ (low-elevation coastal zone) has been used in recent years with reference to specific area and population up to 10 m elevation (Vafeidis *et al.*, 2011). This chapter does not consider the polar coasts (chapter 28), small islands (chapter 29), many of which are low-lying, or the region beyond the continental shelf (chapters 6 and 30).

The coastal systems are conceptualized to consist of both natural systems and human systems (Figure 5-1). The natural systems include distinct coastal characterizations and ecosystems such as rocky coasts, beaches, barriers and sand dunes, estuaries and lagoons, deltas, wetlands and coral reefs. These elements help to define the seaward and landward boundaries of the coast. While they provde a wide variety of regulating, provisioning, supporting and cultural services (MEA, 2005) they have been altered and heavily influenced by human activities with climate change constituting only one amongst many pressures these systems are facing. The human systems include the built environment (settlements, infrastructure and transport networks), human activities (e.g., tourism, aquaculture, etc) as well as formal and informal institutions that organize human activities (e.g., policies, laws, customs, norms and culture). Both systems together form a tightly coupled social-ecological system (SES) (Berkes and Folke, 1998; Hopkins *et al.,* 2012).

[INSERT FIGURE 5-1 HERE
Figure 5-1: Schematic diagram indicating the elements of the coastal zone that are considered in this chapter.]

5.3. Drivers

5.3.1. Introduction

In TAR and AR4 changes in climate drivers (any climate-induced factor that directly or indirectly causes a change), including sea level rise, were projected for different SRES emissions scenarios (Nakicenovic and Swart, 2000). Consequently, to date, most of the impacts and vulnerability assessments of climate change in coastal areas are based on SRES A2, A1B, B2 and A1F1 scenarios. Since AR4 a new scenario process has been initiated to replace the SRES scenarios with Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) (Moss *et al.,* 2010). The RCPs are scenarios specifying concentrations, rather than emissions, thereby avoiding differences in concentrations of Long-Lived Greenhouse Gas and aerosol concentrations for the same emissions scenarios that can arise from the use of different models (van Vuuren *et al.,* 2011). For a comparison between RCP and SRES scenarios see WG1, Chapter 1, Box 1.2. In addition, Extended Concentration Pathways (ECPs) have been introduced for the period 2100-2300 (Meinhausen *et al.* 2009) providing the opportunity to assess the long-term commitment to sea-level rise, which is *very likely* to continue beyond 2500 unless global temperature declines (WG1, Chap.1, 13.5.2).

The SSPs provide representative qualitative story lines (narratives) of world development together with quantitative pathways of key socio-economic variables such as GDP and population (O'Neil *et al.*, 2011). A preliminary list of 5 SSPs have been proposed (Arnell *et al.*, 2011; O'Neil *et al.*, 2011) and will be discussed in 5.3.4.1 and work to further refine these is ongoing (Kriegler *et al.* 2012; Van Vuuren *et al.,* 2012). SSPs do not include assumptions about mitigation policy and are thus independent from RCPs in the sense that the same SSP may lead to different concentration levels and hence rises in sea-level depending on the level of mitigation reached (Arnell *et al.,* 2011; O'Neil *et al.*, 2011).

5.3.2. Relative Sea Level Rise

Relative sea level rise poses a significant threat to coastal systems and low-lying areas around the globe leading to inundation and erosion of coastlines, contamination of freshwater reserves and food crops (Nicholls, 2010). Sea level rise due to thermal expansion as the oceans warm, together with meltwater from glaciers, icecaps and ice sheets of Greenland and Antarctica are the major factors that contribute to relative sea level rise globally. However, the subsidence of coastal land due to sediment compaction, subsurface resource extraction (e.g. groundwater, gas and petroleum; Syvitski *et al.*, 2009), glacial isostatic rebound and tectonic movement may also contribute to relative sea level rise locally and therefore requires consideration in coastal impact studies. Sea level impacts are most pronounced during episodes of extreme sea levels and these are discussed in 5.3.3.

5.3.2.1. Global Mean Sea Level

Although sea level change can exhibit large regional variability on different time scales from factors such as climate variability and ocean circulation patterns, it is *very likely* that over the 20th Century, global mean sea level (GMSL) rose at a mean rate between 1.5 to 1.9 mm yr^{-1} and since 1993, at a rate between 2.8 to 3.6 mm yr^{-1}. Ocean thermal expansion and melting of glaciers have been the largest contributors, accounting for over 80% of the MSL rise over the latter period (AR5, Chapter 13). Future contributions to GMSL rise during the 21st century will *very likely* exceed the observed rate for the period 1971–2010 for all RCP scenarios. Sea levels will continue to rise beyond the 21st Century. Projections for sea levels are available for 2200 to 2500 although these are based on fewer and simpler models that include lower resolution coupled climate models for thermal expansion and ice sheet models coupled to climate models to project ice sheet contributions. The basis for the projections are the Extended Concentration Pathways (ECPs) and projections are provided for low, medium and high scenarios which relate to atmospheric GHG concentrations <500 ppm, 500-700 and > 700 ppm respectively (13.5.2). Projections of GMSL for a range of time horizons are summarized in Table 5-1.

[INSERT TABLE 5-1 HERE
Table 5-1: Projections of global mean sea level rise in metres relative to 1986–2005 based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5-95% range is given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available (source: WG1, Chapter 13).]

[INSERT TABLE 5-2 HERE
Table 5-2: Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects (↑ increase; ↓ decrease; ⊄ no change; ? uncertain; ↔ regional variability).]

5.3.2.2. Regional Sea Level

The impacts of sea level rise will not be uniform in space and time. Natural modes of climate variability influence sea levels in different regions of the globe and this will affect the rate of rise on interdecadal time periods. For example in the equatorial Pacific, sea levels can vary from the global mean by up to 40 cm due to ENSO (e.g. Walsh et al, 2012) and this can strongly influence trends on decadal scales. Regional variations in the rate of sea level rise at the coast can arise from climate and ocean dynamical processes such as changes in winds and air pressure, air-sea heat and freshwater fluxes, ocean currents and their steric properties. Changes in gravitational processes due to the redistribution of water mass and changes in the shape of the sea floor also contribute. Although the vast majority of coastlines are experiencing sea level rise, coastlines near current and former glaciers and ice sheets are experiencing sea level fall. Under RCP4.5 and 8.5, it is *very likely* that about 72% and 77% respectively of the world's coastlines will experience a sea level change that is within ±20% of the GMSL change, although some coastlines may experience a rise of up to 50% above the GMSL (AR5, Chapter 13.6).

5.3.2.3. Local Sea Level

As well as long-term vertical land movements from GIA (glacial isostatic adjustment), relative sea level rise due to subsidence of coastal plains can occur through other natural causes. For example, tectonic movements, both sustained and abrupt, have brought about relative changes of sea level. The Tohoku earthquake in 2011 caused subsidence of up to 1.2 m along ~400 km of the Pacific coast of northeast Japan. The Sumatra-Andaman earthquake in 2004 and subsequent earthquakes in 2005 produced vertical deformation ranging from uplift of 3 m to subsidence of 1 m (Briggs *et al.*, 2006). These movements are especially important in coastal zones located near active plate margins.

Anthropogenic causes of relative sea level rise include sediment consolidation from building loads, reduced sediment delivery to the coast and extraction of subsurface resources such as gas, petroleum and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal (e.g. Kolker *et al*., 2010). Syvitski *et al*., (2009) estimate that the majority of the world's largest deltas are currently subsiding at rates that are considerably larger than the current rates of sea level rise because of coastal sediment starvation due to substantial dam building over the 20th century or sediment compaction through natural or anthropogenic activities. Many large cities on deltas and delta plains have subsided during the last 100 years, by up to 5 m in eastern Tokyo, 3 m in Shanghai, 2 m in Bangkok, and 3 m in the Po delta (Nicholls, 2011; Teatini *et al.*, 2011). Loads from massive buildings and other large structures can also increase sediment compaction and subsidence (Mazzotti *et al.*, 2009). Relative sea level rise can exceed GMSL rise by an order of magnitude, reaching more than 10 cm/y and it is estimated that the delta surface area vulnerable to flooding could increase by 50% under projected sea-level rise in the twenty-first century (Syvitski et al, 2009).

5.3.2.4. Summary

Observed trends in mean sea level together with projected increases for 2100 and beyond means that coastal systems and low-lying areas will increasingly experience adverse impacts associated with submergence (*high confidence*). Large spatial variations in the projected sea level rise, together with local factors such as subsidence suggests that relative sea level rise can be much larger than projected GMSL and therefore is an important consideration in impact assessments (*very high confidence*).

5.3.3. Climate-related Drivers

Increasing greenhouse gases in the atmosphere produce changes in the climate system on a range of time scales that impact the coastal physical environment. On shorter time scales, physical coastal impacts such as inundation, erosion and coastal flooding arise from severe storm-induced surges, wave overtopping and erosion. On longer time scales, changes in wind and wave climate can cause changes in sediment transport at the coast that may also lead to erosion or accretion. Natural modes of climate variability, which can affect severe storm behaviour and wind and wave climate, may also undergo anthropogenic changes in the future. Ocean temperatures can affect species distribution and lead to declines in some species thereby leading to changes in coastal biodiversity. CO_2 uptake in the ocean increases ocean acidity and reduces the saturation state of carbonate minerals, essential for shell and skeletal formation in many coastal species. Past and future changes to these physical drivers are discussed in this section.

5.3.3.1. Severe Storms

Severe storms lead to strong winds and regions of low pressure which, over coastal seas can generate storm surges and high waves. The severity of these depends also on the storm's track, regional bathymetry and nearshore hydrodynamics. Tropical cyclones pose a significant threat to coastal population (see Box 5-2), mostly due to the

associated storm surge, which may combine with fresh water flooding due to extreme rainfall (Rappaport, 2000) and increase the extent of coastal flooding. Extratropical cyclones (ETCs) occur throughout the mid latitudes of both hemispheres and their development is linked to large-scale circulation patterns. Assessment of changes in large-scale climate circulation features indicate that there has been a widening of the tropical belt, poleward shift of storm tracks and jet streams and contraction of the polar vortex leading to the assessment that it is *likely* that, in a zonal mean sense, circulation features have moved poleward (Chapter 2). However, both Seneviratne *et al.* (2012) and AR5 concluded that there is *low confidence* regarding regional changes in intensity of extratropical cyclones. With regards to future changes, models tend to agree on a southward shift in the SH storm track and a global reduction of ETC numbers. However there is *high confidence* that the reduction in the global number of extra-tropical cyclones due to global warming will be small (less than a few percent) and hence small compared to natural interannual variability. There is *high confidence* that a small poleward shift is *likely* in the Southern Hemisphere (AR5 Chapter 14) but changes in the Northern Hemisphere are basin specific and of *lower confidencelower confidence*. There is also *low confidence* in the influence on extreme events of storm track changes.

5.3.3.2. Extreme Sea Levels

Extreme sea levels arise from combinations of factors that include astronomical tides, storm surges, wind and swell waves, sea level variations due to interannual variability and Tsunamis, although the latter are tectonic and therefore not related to climate. The frequency of extreme sea levels will be increased by relative sea level rise. Storm surges, caused by falling atmospheric pressures and surface wind stress associated with storms, may also change if storms are affected by climate change.

Recent global (e.g. Menendez and Woodworth, 2010) and regional studies (e.g. Marcos *et al.*, 2009; Haigh *et al.*, 2010, Losada *et al.* 2013) have found that observed trends in extreme sea levels are mainly consistent with mean sea level trends (SREX, indicating that the increasing frequency of extreme events observed so far is related to rising MSL and not to changes in the behaviour of severe storms. Observations of present sea level extremes due to variability of tides and storm surges have been combined with projections of MSL and their uncertainties, to estimate a "sea level allowance" (Hunter, 2012; Hunter *et al*., 2012) . Assuming that sea level extremes follow a simple extreme value distribution (i.e. a Gumbel distribution), projected MSL rises of 0.542 m (the projected MSL rise for 1990-2100 under an A1FI scenario) and 1.0 m require an additional allowance of 26% and 44% MSL respectively to preserve the current frequency of flooding events (Figure 5-2). Such an allowance can be factored into adaptive responses to rising sea levels. It should be noted however that extreme sea level distributions may not follow a simple Gumbel distribution (e.g. Tebaldi *et al.* 2012) due to different factors influencing extreme levels.

[INSERT FIGURE 5-2 HERE
Figure 5-2: Results of global analysis, indicated by dot diameter. a Factor by which frequency of flooding events will increase with a rise in sea level of 0.5 metres (key is left-hand column of dots in the bottom left-hand corner). b Sea-level rise allowance (metres) for 1990–2100 which conserves frequency of flooding events for the IPCC A1FI Projection based on A1FI emission scenario and AR4-adjusted TAR projections (normal distribution with Δz=0.542 m and σ=0.168 m); key is central column of dots in the bottom left-hand corner. c Sea-level rise allowance (metres) for 21st century which conserves frequency of flooding events for the 1.0/1.0 m Projection, based on post-AR4 results (raised cosine distribution with Δz=1.0 m and W/2=1.0 m); key is right-hand column of dots in the bottom left-hand corner.]

Several regional studies have assessed future changes to storm surges using hydrodynamic models forced by climate models. Extratropical studies show strong regional variability and sensitivity to the choice GCM or RCM (e.g. Debenard and Roed, 2008; Wang et al, 2008; Sterl et al, 2009 for the northeast Atlantic and Colberg and McInnes; 2012 for the southern Australian coastline. The effect of tropical cyclone changes on storm surges have also been investigated in a number of regions including Australia's tropical east coast (Harper *et al*.; 2009), Louisiana (Smith *et al*., 2010), Gulf of Mexico, (Mousavi *et al*., 2011), India, (Unnikrishnan *et al*.; 2011) and New York (Lin *et al*., 2012), and methods used and findings vary considerably between the studies. For example Mousavi *et al*., 2011 developed relationships between current climate cyclone intensities and SSTs and used the projected changes in SSTs from climate models to scale the cyclone intensity whereas Lin et al., (2012) use the cyclones simulated in

four climate models that were scaled-up to realistic cyclone numbers via a synthetic cyclone approach. Lin *et al*., (2012) found that 2 of their 4 models produced changes in storm surges comparable to the projected sea level rise while changes in the other two models were dominated by sea level rise. Non-linear interactions between the storm surge and increased sea level conditions were also highlighted in some studies (e.g. Smith *et al.*, 2010; Mousavi *et al.*, 2012).

The small number of regional storm surge studies combined with the different atmospheric forcing factors and modelling approaches means that there is *low confidence* in projections of storm surges. However, there is *high confidence* that extremes will increase with GMSL rise, thereby leading to large increases in the frequency of extreme sea level events by the end of the 21st century (see also Chapter 13).

5.3.3.3. Winds and Waves

In the context of coasts, wind climate determines large-scale wave climate change, which in turn shapes shorelines. Winds influence longshore current regimes and hence upwelling systems (Narayan *et al.*, 2010; Miranda *et al.*, 2012; see also Chapter 6). Energy dissipation via wave breaking contributes to beach erosion, longshore currents, and elevated coastal sea levels through wave set-up and run-up. Changes to wind and wave climate therefore can affect sediment dynamics and shoreline processes (e.g. Aargaard *et al*., 2004; Reguero *et al.*, 2012) while extreme winds and waves associated with storms are a threat to coastal populations. In addition to shorter period wind waves longer period swell, whose energy dominates the wave energy field, poses a significant danger to coastal and offshore structures, (Semedo *et al.*, 2011) and can causes flooding of coastlines with steep shelf margins (Hoeke *et al*. 2013). The coastal impacts of wave climate change are also a function of wave direction and period as well as the coastline itself, which can influence shoaling and refraction.

For observed changes in wind, Seneviratne *et al*., (2012) concluded that there is *low confidence* in trends calculated from measurements of mean and extreme winds and their causes due to the limited length of records and uncertainties associated with different wind measurement techniques. However, WG1 Chapter 3 notes increasing evidence for a strengthening of the wind stress field in the Southern Ocean since the early 1980s from atmospheric reanalyses, satellite observations and island station data. Regional wave climate is strongly related to modes of climate variability (Seneviratne, 2012) and it is *likely* that there have been positive trends in the North Atlantic, North Pacific and Southern Ocean (Chapter 3, see Table 5-1).

Projected changes in mean and extreme winds and waves were assigned *low confidence* (Seneviratne et al, 2012) owing to limited studies. Although there has been an increase in studies addressing wave climate change (Hemer *et al.*, 2013), generally *low confidence* remains in projected wave climate change (except for *medium confidence* over the southern ocean) and this is due to uncertainties in future winds, particularly those associated with storms (see also Chapter 13.7).

5.3.3.4. Sea Surface Temperature

Sea surface temperature has significantly warmed during the past 30 years along more than 70% of the world's coastlines, with highly heterogeneous rates of change both spatially and seasonally (Lima and Wethey, 2012). The average rate is 0.18 ± 0.16°C per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade. These values are larger than in the global ocean where the average of change is about 0.1°C per decade in the upper 75 m of the ocean during the period 1970-2009 (WGI, Chap. 3) and the seasonal shift is -2.3 days per decade (Lima and Wethey, 2012). Extreme events have also been reported. For example, the record high ocean temperatures along the Western Australian coast during the austral summer of 2010/2011, with nearshore temperatures peaking at about 5 °C above average, were unprecedented (Pearce and Feng, 2013). In summary, positive trends in coastal SST's are seen on the majority of coastlines and the rate of rise along coastlines is higher on average than the oceans (*high confidence*, *limited evidence*). Based on projected temperature increases there is *high confidence* that coastal SST's exhibiting positive trends will continue to do so.

5.3.3.5. Ocean Acidification

Anthropogenic ocean acidification refers to the changes in the carbonate chemistry primarily due to the uptake of atmospheric CO2 (Box CC-OA). Seawater pH exhibits a much larger spatial and temporal variability in coastal waters compared to open ocean due to the variable contribution of processes other than CO2 uptake (Duarte *et al.*, 2013) such as upwelling intensity (Feely *et al.*, 2008), deposition of atmospheric nitrogen and sulphur (Doney *et al.*, 2007), carbonate chemistry of riverine waters (Salisbury *et al.*, 2008; Aufdenkampe *et al.*, 2011), as well as inputs of nutrients and organic matter (Borges, 2011; Cai *et al.*, 2011). For example, pH (NBS scale) ranges from 6 to 9 in 24 estuaries (Borges and Abril, 2012) and short-term (hours to weeks) changes of up to 0.5 pH units are not unusual in coastal ecosystems (Hofmann *et al.*, 2011).

Few ocean acidification time series exceed more than 5 years in the coastal ocean (Wootton *et al.*, 2008; Provoost *et al.*, 2010; Waldbusser *et al.*, 2010). Some exhibit considerable differences with the open ocean stations illustrating the fact that anthropogenic ocean acidification can be lessened or enhanced by coastal biogeochemical processes (Borges and Gypens, 2010; Feely *et al.*, 2010).

In more recent years, a phosphorus removal policy limited primary production which led to a decrease in pH much larger than would be expected from the absorption of atmospheric CO_2 alone (-0.016 pH unit yr-1). Under the IS92a CO_2 emission scenario, the global pH (total scale) of coastal waters has been projected decrease from about 8.16 in the year 1850 to 7.83 in 2100 (Lerman *et al.*, 2011) but with considerable spatial variability. For example, using the same CO_2 emission scenario Cai *et al.* (2011) projected that the overall decline in 0.74 pH between pre-industrial time and 2100 in the Northern Gulf of Mexico, a value that is much greater than in the open ocean.

To summarise, seawater pH exhibits considerable temporal and spatial variability in coastal areas compared to open ocean due to additional natural and human influences (*very high confidence*). Coastal acidification is projected to continue but with large and uncertain regional and local variations (*high confidence).*

5.3.3.6. Freshwater Input

Changes in river runoff arise from changes in climate drivers such as precipitation and droughts, complex interactions between changing levels of CO_2, plant physiology and hence evapotranspiration (e.g. Gedney et al, 2006; Betts et al, 2007) and other human drivers such as land-use change, water withdrawal, dam building and other engineered modifications to waterways. Such changes can have multiple effects on coastal systems. Not only are changes in the quantity and quality of runoff relevant but also the temporal distribution. Sudden pulsed discharges of freshwater arising from meltwater or storm-induced runoff into marine systems may impact ecosystems unable to deal with low-salinity water and can affect the efficiency of estuaries to retain or filter material delivered by the rivers. This can result in the delivery of riverine nutrients to coastal sea systems that would otherwise have been processed during transit. Generally higher and more variable river runoff arises from lowered retention due to land clearing (Chapter 4) such as for agricultural purposes and this also associated with increased erosion and sediment yield.

An assessment of run-off trends in 925 of the world's largest ocean-reaching rivers, which account for about 73% of global total runoff, indicates that from 1948–2004 statistically significant trends were present in only one third of gauges and of these two thirds exhibited downward trends and one third upward trends (Dai *et al.*, 2009). Precipitation changes dominate the trends, which for flow discharging into the Pacific, Indian and Atlantic Oceans, is also correlated with ENSO. Positive trends in runoff are more prevalent in the Arctic in winter and spring associated with snow melt. While precipitation change dominates freshwater flows, decreasing trends in river discharge may be further enhanced by human pressures (Dai *et al.*, 2009; Chapter 3.2.3).

Average annual runoff is generally projected to increase at high latitudes and in the wet tropics and projected to decrease in most dry tropical regions (Chapter 3). Shifts to earlier peak flows are also projected in areas affected by snowmelt. However, there are some regions where there is considerable uncertainty in the magnitude and direction

of change, specifically south Asia and large parts of South America. Both the patterns of change and the uncertainty is largely driven by projected changes in precipitation.

To summarise, there is *medium confidence (limited evidence)* in a net declining trend in freshwater input globally although large regional variability exists. Trends are dominated by precipitation changes although human pressures on water supply may enhance downward trends (*medium confidence*). Uncertainty in future changes in run-off is linked to precipitation uncertainty. Runoff is generally projected to increase in high latitudes with earlier peak flows and in the wet tropics and decrease in other tropical regions but with large uncertainty (*medium confidence*).

5.3.4. Human Drivers

Coastal systems are subject to a wide range of non climate-related drivers (e.g., Crain *et al.*, 2009) the impacts of which can interact with climate-related drivers and confound efforts to attribute causes of changes. Some of the major human drivers, i.e. human-induced factors that directly or indirectly cause changes, are briefly reviewed below.

5.3.4.1. Socioeconomic Development

One of the most important drivers of coastal impacts is socio-economic development (SED). The current understanding of possible future SED pathways is described through a preliminary set of five shared socio-economic pathways (SSPs; Arnell *et al.*, 2011; O'Neil *et al.*, 2011). The highest GDP and lowest population numbers are attained under SSP1 (called "Sustainability"), which reflects a world progressing towards sustainability with reduced resource intensity and fossil fuel dependency, and SSP 5 (called "Conventional Development"), which reflects a world oriented toward equitable rapid fossil fuel-dominated development. GDP is lowest and population highest under SSP 3 ("Fragmentation"), which reflects a world fragmented into poor regions with low resource intensity and moderately healthy regions with a high fossil fuel dependency. GDP and population under SSP 4 (Inequality) which is a highly unequal world both within and across countries, follows a similar but less extreme trend compared to SSP 3. SSP 2 (Middle of the Road) reflects a world with medium assumptions between the other four SSPs.

There is *very high confidence* that SED has been one of the major drivers of increasing coastal flood damage through increasing exposure (IPCC SREX) and it is expected that this will also be a major driver of climate and sea-level rise impacts during the 21st century (Nicholls and Cazenave, 2010). Currently, the Low Elevation Coastal Zone (LECZ) constitutes 2% of world's land area but contains 10% of world's population (600 million) and 13% of world's urban population (360 million) based on 2000 estimates (McGranahan *et al.*, 2007). Although these estimates are subject to uncertainties (see Lichter *et al.*, 2011; Mondal and Tatem, 2012), they are indicative of the high exposure of low-lying coastal regions. About 65% of the world's cities with populations of over 5 million are located in the LECZ, including a large number of small island states and densely populated mega-deltas (McGranahan *et al.*, 2007). The top 10 exposed cities in terms of exposed population are Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, Greater New York, Osaka-Kobe, Alexandria and New Orleans (Hanson *et al.*, 2011). In terms of assets exposed, 60% are from the USA, Japan and the Netherlands (Hanson *et al.*, 2011). Comparatively, Asia demonstrates the greatest exposure in terms of population, assets and productivity and the largest increases in exposure through socio-economic development is expected in Asia and Africa (Dasgupta, 2009; Hanson *et al.*, 2011; Kebede and Nicholls, 2012).

For many locations there is *high confidence* that coastal population and assets exposure is growing faster than the national average trends due to coastward migration, coastal industrialization and urbanization (e.g. McGranahan *et al.*, 2007; Smith, 2011; Seto, 2011; WG2 Ch. 8). Coastal net migration has largely taken place in flood- and cyclone-prone areas, which poses a challenge for adaptation (de Sherbinin *et al.*, 2012). These processes and associated land use changes are driven by a combination of many social, economic, and institutional factors including taxes, subsidies, insurance schemes, aesthetic and recreational attractiveness of the coast and increased mobility (Bagstadt *et al.*, 2007; Palmer *et al.*, 2011). In China, the country with the highest exposed population,

urbanization and land reclamation are the major drivers of coastal land-use change (Zhu *et al.*, 2012). Although coastal migration is expected to continue in the coming decades, it is difficult to capture this process in global scenarios as the drivers of migration and urbanization are complex and variable (Black *et al.* 2011).

Socio-economic development also determines the future capacity to adapt. Poor people living in urban informal settlements, of which there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts (Handmer *et al.*, 2012; de Sherbinin *et al.*, 2012). Of the top ten nations classified by population and proportion of population in coastal low-lying areas the majority are in developing countries (Bollman *et al.*, 2010). SED and associated land reclamation are also major drivers of the destruction of coastal wetlands, which also makes human settlements more vulnerable since wetlands act as natural buffers reducing wave and storm impacts on the coast (e.g., Crain *et al.*, 2009; Shepard *et al.*, 2011). Finally, socio-economic development is expected to further exacerbate a number of human pressures on coastal systems related to changes in freshwater input, water-diversion, nutrients and hypoxia, which will be discussed in the following sections.

[INSERT TABLE 5-3 HERE
Table 5-3: Top ten nations with the largest populations and the highest proportions of population in low-lying coastal areas (Countries with fewer than 100,000 inhabitants are not included; 15 SIDs (Small Island Developing States) with total of 423,000 inhabitants are also excluded). Source: Bollman *et al.*, 2010.]

5.3.4.2. Nutrients

Increased nutrient (i.e. nitrogen, phosphorus) loads to coastal systems in many world regions are observed and simulated by regional and global watershed models ((Alexander *et al.*, 2008; Howarth *et al.*, 1996; Seitzinger *et al.*, 2010). River transported anthropogenic nutrients are primarily due to increased fertilizer use for food production and fossil fuel emissions (NOx) (Bouwman *et al.*, 2009; Galloway *et al.*, 2004).

Anthropogenic global loads of biologically reactive dissolved inorganic N and P (DIN, DIP) are about 2 to 3 times larger than natural sources (Seitzinger *et al.*, 2010) resulting in degradation of coastal ecosystems, including hypoxia. Large variations exist between rivers in the magnitude of nutrient loads and their relative sources. Future trends depend on measures to optimize nutrient use in food production and minimize nutrient loss to rivers from agriculture, sewage, and NOx emissions. Using the Millennium Ecosystem Assessment (MEA) scenario with little emphasis on nutrient management, DIN and DIP global discharge increase by about 30% and 55%, respectively, between 2000 and 2050 (Seitzinger *et al.*, 2010). In the most ambitious MEA nutrient management scenario, global river DIN loads decrease slightly and DIP increases by 35%. In summary, nutrient loads have increased in many regions of the world (*high confidence*).

5.3.4.3. Hypoxia

The presence of excessive nutrients in coastal waters, which causes eutrophication and the subsequent decomposition of organic matter is the primary cause of decreased oxygen concentration (hypoxia). Upwelling of low oxygen waters (e.g., Grantham *et al.*, 2004) and ocean warming, which decreases the solubility of oxygen in seawater (Shaffer *et al.*, 2009) are secondary drivers. The oxygen decline rate is greater in the coastal rather than the open ocean (Gilbert *et al.*, 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2010). The number of so-called “dead zones” has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fisheries catches from these areas are generally lower than predicted from nutrient loading alone (Breitburg *et al.*, 2009). Although non-climate anthropogenic factors are responsible for virtually all hypoxia in estuaries and inner continental shelves, climate drivers such as ocean warming, altered hydrological cycles and coastal currents shifts due to changes in wind patterns may interact with eutrophication in the next decades (Rabalais *et al.*, 2010) (*high confidence*).

5.3.4.4. Sediment Delivery

Human activities in drainage basins and coastal plains have impacted the coastal zone by changing sediment delivery to the coast. Sediment trapping behind dams, water diversion for irrigation, and sand and gravel mining in river channels all act to decrease sediment delivery, whereas soil erosion due to land-use changes acts to increase it. In the 1950s, before widespread dam construction, the global discharge of riverine sediment was estimated to have been ~20 Gt yr^{-1} (e.g., Syvitski *et al.*, 2005; Milliman and Farnsworth, 2011), and it has decreased to 12–13 Gt yr^{-1} (Syvitski and Kettner, 2011). Out of 145 major rivers, only 7 showed evidence of an increase in sediment flux while 68 showed significant downward trends (Walling and Fang, 2003). Two stages of drainage basin development have been identified in patterns of sediment delivery: an increase in the early stage due to soil erosion followed by a decrease in later stages due mainly to dam construction (Syvitski, 2008). The number of dams has increased continuously and their distribution has expanded globally. As of early 2011, the world has an estimated 16.7 million reservoirs larger than 0.01 ha with a combined storage capacity of approximately 8070 km^3 (Lehner *et al.*, 2011). Human pressure is the main driver of the observed declining trend in sediment delivery to the coast (*high agreement*). Reduction of sediment delivery to the coast has impacts on river deltas, contributes to shoreline erosion and threatens mangroves and wetlands (Syvitski, 2008) whereas increase delivery due to soil erosion impacts coastal ecosystems.

5.4. Impacts, Vulnerabilities, and Risks

5.4.1. Introduction

The distinction in the meaning of the terms vulnerability and risk is often unclear in current literature (Ch. 1; SREX; WG2 Glossary), with both terms used interchangeably to describe identical methodological approaches (Hinkel, 2010; Wolf, 2011). Therefore in this chapter, literature assessing vulnerability and risk will be treated together. Diverse approaches are applied for assessing impacts, vulnerability and risk. For impacts on natural systems, the key drivers considered are temperature, ocean acidification and sea level and a variety of approaches are applied including field observations of ecosystem features (e.g. biodiversity, reproduction) and functioning (e.g. calcification, primary production), remote sensing (e.g., extent of coral bleaching, surface area of vegetated habitats) and perturbation experiments in the laboratory and in the field. For impacts on human systems, most approaches focus on relative sea-level rise and can be distinguished in terms of the main biophysical impacts they address (Table 5-4).

[INSERT TABLE 5-4 HERE
Table 5-4: Main impacts of relative sea-level rise. Adapted from Nicholls 2002 and Nicholls *et al.* 2010.]

Sea-level rise exposure approaches are applied at all scales to assess values exposed to sea level rise (e.g., people, assets, ecosystems or geomorphological units). *Submergence exposure approaches* assess exposure to permanent inundation under a given level of sea level rise (e.g., Dasgupta *et al.*, 2008; Boateng, 2012) whereas *flood exposure approaches* assess exposure to temporary inundation during a coastal flood event by combining the extreme water level of the flood event with a given level of sea level rise (e.g., Dasgupta *et al.*, 2009; Kebede and Nicholls, 2012).

Indicator-based approaches are also used at all scales to aggregate data on the current state of the coastal systems into vulnerability indices (Hinkel, 2012), based on either biophysical exposure or hazard variables (e.g., Yin *et al.*, 2012; Bosom and Jimenez, 2011), socioeconomic variables representing a social group's capacity to adapt (e.g., Cinner *et al.*, 2012) or both kinds of variables (e.g., Bjarnadottir *et al.*, 2011; Yoo *et al.*, 2012; Li and Li, 2012).

At local scales (10-100 km coastal length), *process-based models* are applied to assess flooding, erosion and wetland impacts. Approaches include assessments of *flood damage* of single extreme water level events using *hydrodynamic/inundation models* (e.g., Xia *et al.*, 2011; Lewis *et al.*, 2011). M*orphodynamic models* are applied to assess impacts of RSLR on coastal erosion *(*Jiménez *et al. 2009;* Ranasinghe *et al. 2012).* For ecosystem impacts *ecological landscape simulation models* are used to predict habitat change due to sea level rise and other factors (e.g., Costanza *et al.*, 1990, Costanza and Ruth, 1998).

For assessing the impacts of sea level rise at regional to global scales (>1000 km coastal length), heuristic, statistical and economic models together with damage functions are used, as detailed process-based models are not available due to data and computational limits. Global scales assessments have been conducted with the Integrated Assessment Model FUND (Anthoff *et al.*, 2010) and the impact model DIVA (Hinkel and Klein, 2009). These models and their results are discussed in 5.4.3.1 and 5.5.3.

In the impacts on, vulnerabilities of and risks to biophysical systems (5.4.2) and for human systems (5.4.3) are covered. For biophysical systems, we start with impacts on smaller scale systems (e.g., beaches, wetlands, etc.) and proceed to larger scale and compound systems (estuaries and deltas). For human systems, we start with impacts on human settlements as a whole followed by impacts on key sectors that support human settlements. Where possible, all subsections address drivers, observed and projected changes.

5.4.2. Natural Systems

Coastal ecosystems are experiencing large cumulative impact of human activities (Halpern *et al.*, 2008) arising from both land- and ocean-based anthropogenic drivers. Anthropogenic drivers associated with global climate change are distributed widely and are an important component of cumulative impacts experienced by coastal ecosystems. There are few wetlands, mangroves, estuaries, rocky shores or coral reefs that are not exhibiting some degree of impact. Overexploitation and habitat destruction are often the primary causes of historical changes in coastal systems and eutrophication has largely followed rather than driven observed declines in diversity, structure, and functioning (Lotze *et al.*, 2006). Further, extreme climate events generate changes to both the mean and the variance of climatic variables over ecological time scales.

5.4.2.1. Beaches, Barriers, and Sand Dunes

Beaches, barriers and sand dunes constitute about one-third of world's coasts. These dynamic systems often exhibit distinct diurnal and seasonal changes. Due to their attractive attributes, they are highly valued for their recreational and residential value.

Observed impacts

Globally beaches and dunes have in general undergone net erosion over the past century or longer (e.g. see Bird, 2000 for an overview). This erosion is due to a variety of processes with some climate related: rising sea levels (Ranasinghe and Stive, 2009); increases in the frequency of extreme water levels with sea-level rise (Tebaldi *et al.*, 2012); wave propagation caused by sea-level changes realigning shorelines (Tamura *et al.*, 2010); sustained changes in the direction of mean wave energy (Reguero *et al.*, 2013); increased storm waves (Stutz and Pilkey, 2011) and changes in the loss of natural protective structures such as coral reefs (Grevelle and Mimura, 2008) or mangrove forests (Bongaerts *et al.*, 2010). These processes may act at different time scales.

Reasonably accurate maps have been available since about the mid-19th century to compare with more recent maps and imagery to quantify combined climate and non-climate changes. For example, along the U.S. Mid-Atlantic and New England coasts the long-term rate of erosion is 0.5 ± 0.09 m yr^{-1} and 68% showed net erosion based on over 21,000 measurement locations equally spaced along more than 1,000 km of coast (Hapke *et al.*, 2011). However, a survey using historical aerial photographs and satellite images of 27 atoll islands in the central Pacific showed that 86% of the islands have remained stable or increased in area over a 19 to 61 year period, contradicting the widespread perception that small islands are eroding with sea-level rise (Webb and Kench, 2010).

Attributing shoreline changes to climate change is still difficult due to the multiple natural and anthropogenic drivers contributing to coastal erosion. For example, rotation of pocket beaches (i.e. where one end of the beach accretes while the other erodes and then the pattern reverses) of Southeast Australia is closely related to interannual changes

in swell direction (Harley *et al.*, 2010). Additional processes, unrelated to climate change, that contribute to coastal change, include dams capturing fluvial sand (e.g., in Morocco, Chaibi and Sedrati, 2009). Statistically linking sea-level rise to observed magnitudes of beach erosion has been challenging as the coastal sea-level change signal is small relative to other processes (e.g. Sallenger *et al.*, 2000; Leatherman *et al.*, 2000a; 2000b). A Bayesian network incorporating a variety of factors affecting coastal change including relative sea-level rise, has been successful in hindcasting shoreline change, and, hence, may be useful in forecasting change (Gutierrez *et al.*, 2011).

One observed impact of net erosion is clear. Where an eroding shoreline approaches hard, immobile, structures like seawalls or resistant natural cliffs, the beaches will narrow due to coastal squeeze that removes the sands and associated habitats, and potentially steepens the beach slope, impacting the survivability of a variety of organisms (Jackson and McIlvenny, 2011). With coastal squeeze, sand dunes will ultimately be removed as the beach erodes and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them to inundation and further change if recovery does not occur before the next storm (Plant *et al.*, 2010).

Projected impacts

Projected sea-level rise may approach 1 m or more by 2100, and in the intervening time the resulting inundation and erosion may become detectable and progressively important. The impacts will *likely* be first apparent by sea-level rise adding to storm surge, making extreme water levels higher and more frequent to attack beaches and dunes (Tebaldi *et al.*, 2012).

Some investigators have used the Bruun rule to calculate erosion by sea-level rise (Bruun, 1962), although there is disagreement about whether the Bruun rule is appropriate (Cooper and Pilkey, 2004; Woodroffe and Murray-Wallace 2012). How to calculate the amount of retreat remains controversial (Gutierrez *et al.*, 2011; Ranasinghe *et al.*, 2012). An increase in storm intensity and ocean swell may accelerate erosion of beaches, barriers and dunes although in places beach response to sea-level rise could be more complex than simple retreat (Irish *et al.*, 2010).

Coastal squeeze will *likely* accelerate with a rising sea level. In many locales, locating sufficient sand to artificially rebuild beaches and dunes will *likely* become increasingly difficult as present supplies near to project sites are depleted. New generation models are emerging to estimate the costs of saving oceanfront homes through beach nourishment relative to the structures cost (McNamara *et al*, 2011). In the absence of adaptation measures, beaches and sand dunes currently affected by erosion will continue to do so under increasing sea levels (*high confidence*).

5.4.2.2. Rocky Shores

According to Davis and FitzGerald (2004) three-quarters of the world's coasts are rocky. They vary from consolidated sediments (lithified coasts) to unconsolidated sediments (unlithified coasts), with different strengths and typically having an abrasional shore platform at their base. They are characterized by very strong environmental gradients, especially in the intertidal zone where challenges are posed by both aquatic and aerial climatic regimes, such as temperature and desiccation

Observed impacts

Cliffs and platforms are erosional features and any change in the climate system that increases the efficiency of processes to act on them, such as relative sea level rise will lead to increased rates of erosion (Naylor *et al.*, 2010). Other significant climate drivers include mid-latitude storminess, wave climate and rainfall regime on cliff dynamics and retreat rates (Brooks and Spencer, 2012). Precipitation and frost appear to have a limited role in cliff retreat (Dornbusch *et al.*, 2008).

Cliffs and platforms have reduced resilience to climate change impacts; once platforms are lowered or cliffs retreat, it is difficult to rebuild them (Naylor *et al.*, 2010). For cohesive clay coasts, rising sea level will usually result in accelerated rates of bluff recession, especially if the rise is rapid (Trenhaile, 2010).

Changes in the abundance and distribution of rocky shore animals and algae in rocky shores have long been recognized (Hawkins *et al.*, 2008) and perturbation experiments provided information about environmental limits, acclimation and adaptation, particularly to changes in temperature (Somero, 2012). The challenge is to distinguish the response that are due to climatic drivers from those due non-climatic drivers, or to natural temporal and spatial fluctuations.

Helmuth *et al.* (2006) reported shifts of range limits of many intertidal species of up to 50 km per decade, much faster than most recorded shifts of terrestrial species. However, the geographical distribution of some species has not changed in recent decades, may be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding effects of variables such as timing of low tide, hydrographic features, lack of suitable substrata, poor larval dispersal, and effects of food supply, predation and competition (Helmuth *et al.*, 2002, 2006; Poloczanska *et al.*, 2011).

The dramatic decline of biodiversity in mussel beds of the Californian coast, with a 59% loss in species richness between the 1960s and 2002, has been attributed to large-scale processes associated with climate change (*high confidence*; Smith *et al.*, 2002). A strong impact of temperature and food availability was shown in mussels on the coast of Oregon, with higher growth during warm than cool events (Menge *et al.*, 2008). Warming also reduced predator-free space on rocky shores, which lead to a decrease of the vertical extent of mussel beds by 51% in 52 years in the Salish Sea, and the disappearance of reproductive populations of mussels at several sites, illustrating the alteration of interspecific interactions by climate change (Harley, 2011).

Rocky shores are one of the few ecosystems for which field evidence of the effects of ocean acidification is available. Observational and modeling analysis have shown that the community structure of a rocky shore site of the NE Pacific shifted from a mussel to an algal-barnacledominated community between 2000 and 2008 (Wootton *et al.*, 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).

Projected impacts

Based on contemporary and historic data for shoreline retreat the major driver appears to be sea-level rise (Brooks and Spencer, 2012). Soft-rock recession rates can be estimated by using square root of the relative change in sea-level rise rate while cliff retreat depends not only on total elevation change of sea level but also on the rate of sea-level rise (Ashton *et al.*, 2011).

In a modelling study, Trenhaile (2011) found sea-level rise to trigger faster rates of cliff recession, especially in coasts that are already retreating fast. However, results further suggested that coasts currently retreating slowly would experience the largest proportional increases in retreat rates. Increases in storminess appear to have smaller effects on rocky shores (Trenhaile, 2011; Dawson *et al.*, 2009). Using existing topographical data and a digital elevation model, the intertidal areas of rocky shore in Scotland are estimated to decrease by 10-27% with a 0.3 sea-level rise (Jackson and MacIlvenny, 2011).

Most projections of the effect of climate change on rocky shore ecosystems have used a climate envelope approach using environmental tolerances obtained in laboratory perturbation experiments and assuming that species will remain in their bioclimatic envelope as climatic stressors change. Few have considered the effects of direct and indirect species interactions (Poloczanska *et al.*, 2008; Harley *et al.*, 2011) and the effects of multiple stressors (Helmuth *et al.* 2006).

The abundance and distribution of rocky shore species will continue to vary in a warming world (*high confidence*). The likely long-term consequences of ocean warming on mussel beds of the NE Pacific are both positive (increased growth) and negative (increased susceptibility to stress and of exposure to predation)(*medium confidence*; Smith *et*

al., 2002; Menge *et al.*, 2008). Importantly, these projections are conservative as they do not consider hypoxia (Grantham *et al.*, 2004) or ocean acidification (Feely *et al.*, 2008) which is known to occur in this area.

Despite some shortcomings (Riebesell, 2008), observations performed near natural CO_2 vents in the Mediterranean Sea show that diversity, biomass, and trophic complexity rocky shore communities will decrease at future pH levels (*high confidence*; Barry *et al.*, 2011; Kroeker *et al.*, 2011). An abundant food supply tolerance appears to enable mussels of the Baltic Sea to tolerate low pH (Thomsen *et al.*, 2010, 2012) at the cost of increased energy expenditure. Model projections that assume a linear increase in temperature and ocean acidity, and include the interactive effects of temperature and pH suggests that a local population of a barnacle will become extinct in the English Channel 10 years earlier than would occur if there was only global warming and no concomitant decrease in pH (*medium confidence*; Findlay *et al.*, 2010).

Rising sea level is the major driver for rocky shores retreat (*robust evidence*). With coral reefs, rocky shores are the coastal ecosystem for which there is most evidence of the impacts of climate change. The most prominent effects are range shifts of species in response to ocean warming (*high confidence*) and changes in biodiversity (*high confidence*) in relation to ocean warming and acidification.

5.4.2.3. Wetland and Seagrasses Beds

Vegetated coastal habitats, including mangrove forests, salt marshes, seagrass meadows and macroalgal beds occur as a thin vegetation belt fringing the shoreline (Hemminga and Duarte 2000). Coastal wetlands are prominent features and important habitats in the intertidal zone along the coastline, including mangrove forests and tidal marshes. Seagrass meadows and macroalgal beds extend from the intertidal to the subtidal areas in coastal areas.

Observed impacts

Mangrove forests, salt marshes and seagrass meadows are declining globally (Duarte *et al.*, 2005), rendering shorelines more vulnerable to erosion due increased sea level rise and increased wave action (e.g., Alongi, 2008) and leading to the loss of carbon stored in sediments. Together, the loss of coastal wetlands and seagrass meadows results in the release of 0.04 to 0.28 Pg C annually from organic deposits (Pendleton *et al.* 2012). Recognition of the important consequences of the loss of mangrove forests, salt marshes and seagrass meadows for coastal protection and carbon burial, has led to large-scale reforestation efforts in some nations (e.g. Thailand, India, Vietnam).

The response of saltmarsh to sea level rise involves landward migration of salt marsh vegetation zones and submergence at lower elevations and drowning of interior marshes. Ocean warming is leading to range shifts in vegetated coastal habitats. The poleward limit of mangrove forests is generally set by the 20 ºC mean winter isotherm (Duke *et al.*, 1998). Accordingly, migration of the isotherm with climate change (Burrows *et al.*, 2011) should lead to a poleward expansion of mangrove forests, as observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux *et al.*, 2011, Raabe *et al.* 2012), and New Zealand (Stokes *et al.*, 2010), where it leads to increased sediment accretion (*medium confidence*).

Seagrass meadows are already under stress due to climate change (*high confidence*), particularly where maximum temperatures already approach their physiological limit. Heat waves lead to widespread seagrass mortality, as documented for Zostera species in the Atlantic (Reusch *et al.*, 2005), and Posidonia meadows in the Mediterranean Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011) (*high confidence*). Warming also favours flowering of P. oceanica (Diaz-Almela *et al.*, 2007), but the increased recruitment rate is insufficient to compensate for the losses resulting from elevated temperature (Diaz-Almela *et al.*, 2009).

Kelp forests have been reported to decline in temperate areas in both hemispheres (Johnson *et al.* 2011, Wernberg *et al.* 2011a,b, Fernández *et al.* 2011), a loss believed to involve climate change (*high confidence*). Decline in kelp populations attributed to ocean warming has been reported in southern Australia (Johnson *et al.* 2011, Wernberg *et*

al. 2011a,b) and the North Coast of Spain (Fernández *et al.* 2011). The spread of subtropical invasive macroalgal species is believed to be facilitated by climate change, adding to the stresses temperate seagrass meadows experience from ocean warming (*medium evidence, high agreement*).

Projected impacts

Ocean acidification (5.3.34; Box CC-OA) is expected to enhance the production of seagrass (Duarte, 2000, McKee *et al.* 2012) and macroalgae (Wu *et al.*, 2008) through the fertilization effect of CO_2. Increased CO_2 concentrations may have already increased seagrass photosynthetic rates by 20% (Hemminga and Duarte, 2000; Hendriks *et al.*, 2010) (*limited evidence, high agreement*).

Coupling of downscaled model projections using the A1B scenario in the Western Mediterranean along with empirically-determined relationships between mortality rates and maximum seawater temperature led Jordá *et al.* (2012) to conclude that seagrass, Posidonia oceanica, meadows may become functionally extinct by 2050 to 2060 (*high confidence*). Poleward range shifts in vegetated coastal habitats is expected to continue with climate change (*high confidence*). Reduced ice cover and retreat of coastal glaciers may facilitate the expansion of seagrass meadows and kelp forests along the Arctic (Krause-Jensen *et al.* 2012; *medium confidence*), with cascading effects on the coastal Arctic ecosystem (Krause-Jensen *et al.* 2012).

Elevated CO_2 and ocean acidification are expected to lead to increased productivity of vegetated coastal habitats in the future (Duarte *et al.* 2000) (*high confidence*). However, there is *limited evidence* that elevated CO_2 may increase seagrass survival or resistance to warming (Alexandre *et al.*, 2012; Jordá *et al.*, 2012).

Coastal wetlands and seagrass meadows experience coastal squeeze in urbanized coastline, with no opportunity to migrate inland with rising sea levels. However, increased CO_2 and warming can stimulate marsh elevation gain, counterbalancing moderate increases in rates of sea-level rise (Langley *et al.*, 2009; Kirwan and Mudd, 2012). The net impact of climate change on salt-marsh accretion will be to increase carbon burial rates in the first half of the twenty-first century, with carbon–climate feedbacks diminishing over time (Kirwan and Mudd, 2012) (*medium confidence*).

In summary, climate change will significantly contribute to the continued decline in the extent of seagrass and kelps in the temperate zone (*medium confidence*) and the range of seagrass, mangroves and kelp in the northern hemisphere will expand poleward (*high confidence*). The limited positive impact of warming and increased CO_2 on some vegetated ecosystems will be insufficient to compensate the decline of their extent resulting from other human drivers such as land use change (*very high confidence*).

5.4.2.4. Coral Reefs

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building corals and encrusting macroalgae. They are among the most diverse ecosystems and are sources of many benefits through key services provided to humans.

Observed impacts

Coral reefs are susceptible to climate-related and non climated-related processes (see Box CC-CR). Mass coral bleaching has occurred in association with positive temperature anomalies over the past 30 years, sometimes followed by mass mortality (Hoegh-Guldberg, 1999; Kleypas *et al.*, 2008; Baker *et al.*, 2008). Bleaching events are variable in time and space: 7% of the grid cells comprising reefs exhibited at least one bleaching event in 1985-1994 compared to 38% in the subsequent decade due to intense El Niño events. Recovery from the 1998 global bleaching event was generally slow in the Indian Ocean (about 1% yr^{-1}), absent in the western Atlantic and variable elsewhere (Baker *et al.*, 2008).

Warming causes a poleward range expansion of some corals (*high confidence*; Greenstein and Pandolfi, 2008; Yamano *et al.*, 2011). The paleontological record suggests that the observed poleward range extension may soon be followed by equatorial range retractions (Kiessling *et al.*, 2012). Several reef crises of the last 500 Myr were at least partially governed by ocean acidification and warming (Kiessling and Simpson, 2011). Ocean acidification (5.3.3.5, Box CC-OA) has become a recent source of concern because persistence of coral reefs directly depends on the balance between the production and erosion of calcium carbonate (Andersson and Gledhill, 2013). It generally decreases calcification (Kroeker *et al.*, in press) and promotes dissolution of calcium carbonate and bioerosion (Tribollet *et al.*, 2009; Wisshak *et al.*, 2012), leading to a transition from net accretion to net erosion and to poorly cemented reefs (Manzello *et al.*, 2008).

Lower pH decreases calcification in many reef-building corals and coralline algae (Andersson *et al.*, 2011) and may have already decreased (e.g., Gattuso *et al.*, 1999; Silverman *et al.*, 2009) and most (e.g., De'ath *et al.*, 2009, Manzello, 2010) retrospective studies show decreased calcification in recent decades. Attribution has proven difficult but warming rather than acidification appears to be the primary driver (*medium confidence*; Cooper *et al.*, 2012).

Climate-related drivers other than ocean warming and acidification do not seem to have led to any obvious changes since the industrial revolution (*high confidence*). Coral reef growth is intimately linked to sea level but, within the uncertainties of past sea level rise and coral reef growth, most coral reefs seem to have kept pace with the recent sea-level rise (Buddemeier and Smith, 1988).

Projected impacts

The frequency and magnitude of coral bleaching and mortality will increase in the next few decades (*very high confidence*; Hoegh-Guldberg, 1999; Donner *et al.*, 2009; Chapter 30, 30.8.2). Under the A1B CO_2 emission scenario, 99% of the grid cells experience at least one severe bleaching event over 2090-2099 (Figure 5-3; Teneva *et al.*, 2011). Half of the coral reefs may avoid high frequency bleaching through 2100 assuming hypothetical acclimation and/or adaptation (*limited evidence, low agreement*; Logan *et al.*, sbm).

[INSERT FIGURE 5-3 HERE
Figure 5-3: Percent of reef locations (1°x1° grid cells which have coral reefs) that experience no bleaching, at least one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are summarized from the ReefBase dataset (Kleypas *et al.* 2008). In the observations, some of the "no bleaching" cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the SRES A1B CO_2 scenario and the standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are not shown.]

Ocean acidification reduces biodiversity and favours seagrasses and fleshy algae against corals (Fabricius *et al.*, 2011). Since the effects of elevated temperature and acidity are synergistic in several reef-builders (Reynaud *et al.*, 2003; Anthony *et al.*, 2008), their combined impact may be larger than those observed near CO_2 vents today (*high confidence*). Ocean warming and acidification expected under RCP 8.5 will reduce calcification, elevate coral mortality and enhance sediment dissolution (*high confidence*; Manzello *et al.*, 2008). Coral reefs may stop growing and start dissolving when atmospheric CO_2 reaches 560 ppm due to the combined effects of both drivers (*medium evidence*; Silverman *et al.*, 2009).

The maximum rate of vertical accretion has been variable regionally during the last deglaciation (about 20 mm yr^{-1}; Dullo, 2005; Montaggioni *et al.*, 2005) and has not enabled all coral reefs to keep-up with sea level rise. Some reefs kept-up, even when the eustatic sea level rise exceeded 40 mm yr^{-1} (Camoin *et al.*, 2012). Therefore, a number of coral reefs could keep up with the maximum rate of sea level rise of 15.1 mm yr^{-1} projected at the end of the century (WGI, Table 13.5; *medium confidence*). A lower net accretion than during the Holocene, as reported for Caribbean

reefs (Perry *et al.*, 2013) weaken this capability. *high confidence*Reef submergence would increase turbidity leading to increased stress (Storlazzi *et al.*, 2011).

In summary, climate-related drivers are the primary cause of mass coral bleaching and mortality (*very high confidence*) and deteriorate the balance between coral reef construction and erosion (*high confidence*). The future magnitude of these effects will depend on the rates of warming and acidification (*very high confidence*), with a moderating role of biological acclimation and adaptation which appears limited (*medium confidence*).

5.4.2.5. Coastal Aquifers

A coastal aquifer is an underground layer of water-bearing permeable rock or unconsolidated materials from which groundwater can be extracted. Consequently, they are of strategic importance for the water supply of highly populated coastal areas, especially in small islands (Chap. 29, 29.3).

Observed impacts

Coastal aquifers are very sensitive to a range of climate and non climate-related drivers. Temperature and evaporation rise, changes in precipitation and extended droughts that affect aquifer recharge are some of the factors that can contribute to displacement of fresh groundwater by more saline water. Rising sea levels and partial or complete overwash from storm waves or storm surge are also relevant drivers, especially in low-lying areas and islands (Terry and Falkland, 2010, White and Falkland, 2010, Post and Abarca, 2010).

Combined with this, excessive groundwater extraction for coastal settlements and agriculture causes intrusion of saline water from the ocean or from deeper, more saline layers below the aquifer. For example, coastal aquifers on the east and west coasts of the US have experienced increased levels of salinity largely due to excessive anthropogenic water extraction (Barlow and Reichard, 2011). The combination of natural with anthropogenic drivers of over-extraction, pollution, mining for building and erosion due to shoreline works compound groundwater supply problems in small tropical islands in the Pacific, Indian and Atlantic Oceans (White *et al.*, 2007; White and Falkland, 2010). Detailed information on salinization observations in small islands can be found in Chapter 29.

Attribution of saline intrusion to incremental sea level rise is still not sufficiently supported (Rozell and Wong, 2010; White and Falkland 2010). In small islands, observed saltwater intrusion due to flooding and overwash under storm events cannot be attributed to climate change (Chap. 29). Furthermore, Werner (2010) noted that there are fundamental knowledge gaps that impede assessment of changes in seawater intrusion, which are mostly due to uncertainties in the predictive capabilities of the models, limitations in the assessment of small-scale processes and difficulties in characterizing the marine-groundwater interactions.

Projected impacts

The assessment of climate change impacts that may arise from changes in ground water recharge and sea level rise is still challenging, limiting the work currently available on climate change projected impacts on coastal aquifers. Rozell and Wong, 2010 assessed the impact of rising sea levels on fresh water resources on Shelter Island (USA) for two different combinations of precipitation change and sea level rise. Results show that projected impacts were highly dependent on local conditions. Based on a simplified analytical model Ferguson and Gleeson (2012) concluded that the direct impact of groundwater extraction has been and will be much more significant than the impact of sea level rise under a wide range of hydrogeolic conditions and population densities.

In summary, there is *very high confidence* that increased usage of groundwater resources for agriculture and coastal settlements globally has led to a reduction in groundwater quality, including increased salinization (*high agreement, robust evidence*). Human-induced pressure will continue to be the main driver for aquifer salinization (*high*

agreement). Climate change through changing patterns of precipitation, increased storminess and sea level rise will exacerbate these problems (*high agreement, limited evidence*).

5.4.2.6. Estuaries and Lagoons

Coastal lagoons are shallow water bodies separated from the ocean by a barrier and connected at least intermittently to the ocean, while estuaries are the primary conduit for water, nutrients and particulates from land to the sea.

Observed impacts

Sediment accumulation in estuaries is generally very high because of riverine particle delivery but heterogeneous and habitat-specific. Changes in sediment accumulation is directly affected by human drivers, such as dredging, and indirectly via habitat loss, changes in sea-level, storminess and sediment supply by rivers (Syvitski *et al.*, 2005). Coastal lagoons are also highly susceptible to alterations of sediment input and erosional processes driven by changes in sea level, precipitation, and storminess (Pickey and Young, 2009). Estuarine water with low tidal range are strongly affected by changes in run-off since the residence time depends on the relative strengths of runoff and tidal forcing and governs many ecosystem processes including nutrient processing, the metabolic balance, carbon dioxide exchange and hypoxia (Howarth *et al.*, 2009; Canuel *et al.*, 2012). River floods and other runoff events have been reported to impact estuarine communities and deliver large quantities of organic matter to coastal systems, controlling the cycling of organic matter and nutrients (Canuel *et al.*, 2012; Statham, 2012).

Enhanced nutrient delivery (5.3.4.3) has resulted in major changes in biogeochemical processes, community structure and ecosystem functions (Howarth *et al.* 2009), including enhanced primary production which has affected coastal fishery yield (Nixon, 1982; Savage *et al.*, 2012). Eutrophication has modified food-web structure (*high confidence*) and led to more intense and longer lasting hypoxia (5.3.4.4), more frequent occurrence of harmful algal blooms (*high confidence*; Breitburg *et al.*, 2009; Howarth *et al.*, 2009) and to enhanced emission of nitrous oxide (*high confidence*; Kroeze *et al.*, 2010; de Bie *et al.*, 2002).

Projected impacts

The increase of atmospheric carbon dioxide levels will reduce the efflux of CO_2 from estuaries (Borges, 2005; Chen and Borges, 2009; *high confidence*). Its impact on the pH of estuarine and lagoon waters will generally be limited because other drivers are generally more important (*high confidence;* 5.3.3.4 and Box CC-OA). For example, recent changes in the freshwater flow in the Scheldt estuary was the main factor controlling pH, either directly via a decreased supply of dissolved inorganic carbon and total alkalinity, and, indirectly, via the decreased input ammonia loadings and lower rates of nitrification (Hofmann *et al.*, 2009).

Sea-level rise will have likely impact sediment redistribution, the partitioning of habitats within estuaries and landward lagoon extension (*high confidence*; Anthony *et al.*, 2009) Lagoons may shrink because landward migration is restricted due to human occupation on the landward side (Pilkey and Young, 2009: Anthony *et al.*, 2010; Stutz and Pilkey, 2011).

Changes in hydrology could affect lagoons and estuaries in multiple ways. The water residence time could either increase or decrease, depending on direction and magnitude of changes in discharge and precipitation-evaporation balance (Anthony *et al.*, 2009) with diverging impacts on primary production, fisheries and aquaculture (Smith *et al.*, 2005b; Webster and Harris, 2004; Canu *et al.*, 2010). Altered riverine discharge may affect estuarine stratification with consequences for ecosystem metabolic balances, intensity and occurrence of biogeochemical processes, organism distribution patterns and frequency and duration of hypoxia (Hong and Shen, 2012; Rabalais *et al.*, 2009). However, stronger winds and droughts may reduce the extent, duration and frequency of estuarine stratification, counteracting the decrease in oxygen concentration (*medium confidence*; Rabalais *et al.*, 2009). Changes in precipitation extremes and freshwater supply may induce dramatic fluctuations in salinity with

associated dverse impacts on benthic macrofauna and ecosystem functions (Pollack *et al.*, 2011; Levinton *et al.*, 2011; Fujii and Raffaelli, 2008; Jeppesen *et al.*, 2007).

Warming will lead to enhanced stratification of estuaries and lagoons, increasing hypoxia (*medium confidence*; Diaz and Rosenberg, 2008; Rabalais *et al.*, 2009). It will also directly affect most biological processes and the trophic status of coastal ecosystem, and higher carbon dioxide emission (*limited evidence, medium agreement*; Canuel *et al.*, 2011). Warming will lengthen the duration of phytoplankton production season (Cloern and Jassby, 2008; *medium confidence*).

Changes in storm events would alter the extent and duration of estuarine stratification (Hong and Shen, 2012), the sediment deposition-erosion balance of lagoons and estuaries (Pilkey and Young, 2009), the structure and functioning of biological communities via the transport of communities and/or of their resources, and the underwater light climate (*medium confidence*; Wetz and Paerl, 2008; Canuel *et al.*, 2012).

Finally, any change in the primary production of lagoons will impact fisheries as there is an empirical correlation between primary production and fisheries yield (*limited evidence, medium agreement*; Nixon, 1982). For example, seawater warming and changes in seasonal patterns of precipitations projected in the Venice lagoon using the SRES A2 CO_2 emission scenario for the period 2071-2100, leads to a reduction in plankton production, a decline of habitat suitability for clam growth and aquaculture (Canu *et al.*, 2010).

In summary, the primary drivers of change in lagoons and estuaries are human drivers rather than climate change (*very high confidence*). Future changes in climate-related drivers such as warming, acidification, waves, storms, sea level and run-off will have consequences on the functions and services of ecosystems in lagoons and estuaries (*high confidence*) but the impacts cannot be assessed at the global scale as the key drivers operate at a local to regional scale.

5.4.2.7. Deltas

Deltas are low-lying coastal landforms formed by riverine sediments in the areas around river mouths, mostly during the last 6000–7000 years of relatively stable sea level. They are characterized by interplay between rivers, lands, and oceans and are influenced by a combination of river, tidal, and wave processes. Deltas are a coastal complex that combines natural systems in diverse habitats (e.g., tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying wetlands) and human systems (e.g., houses, agriculture, aquaculture, industry, and transport). They have a population density more than 10 times the world average (Ericson *et al.*, 2006; Foufoula-Georgiou *et al.*, 2011). As low-lying plains, deltas are highly sensitive to changes in sea level. Deltas are subject to climatic impacts from rivers upstream (e.g., freshwater input) and oceans downstream (e.g., sea-level changes, waves) as well as within the deltas themselves. At the same time, they are affected by human activities such as land-use changes, dam construction, irrigation, mining, extraction of subsurface resources, and urbanization (Nicholls *et al.*, 2007).

Observed impacts

The combined impact of sediment reduction, relative sea-level rise, land-use changes in deltas, and river management on channels and banks has led to the widespread degradation of deltas (*very high confidence*). Decreased sediment discharge due to dam construction and irrigation creates an imbalance in sediment budget in coastal zones. Degradation of beaches, mangroves, tidal flats, and subaqueous delta front along deltaic coasts has been reported in many deltas (*very high confidence*)(e.g., Nile and Ebro, Sanchez-Arcilla *et al.*, 1998; Po, Simeoni and Corbau, 2009; Krishna-Godavari, Nageswara Rao *et al.*, 2010; Changjiang, Yang *et al.*, 2011; Huanghe, Chu *et al.*, 1996). Deltaic coasts naturally evolve by seaward migration of the shoreline, forming a delta plain; however, decreasing sediment discharge during the last 50 years has decreased the growth of deltaic land, even reversing it in some locations (e.g., Nile, Godavari, Huanghe). Artificial reinforcement of natural levees also has reduced the interdistributary basin sedimentation in most deltas, resulting in wetland loss.

The major impacts of sea-level rise are changes in coastal wetlands, increased coastal flooding, increased coastal erosion, and saltwater intrusion into estuaries and deltas (Mcleod *et al.*, 2010b), which are exacerbated by increased human-induced drivers (*very high confidence*). Ground subsidence amplifies these hazards in farms and cities on deltaic plains through relative sea-level rise (Day and Giosan, 2008; Mazzotti *et al.*, 2009). Relative sea-level rise due to subsidence has induced wetland loss and shoreline retreat (*high confidence*)(e.g., the Mississippi delta Morton *et al.*, 2005; Chao Phraya delta, Saito *et al.*, 2007). Episodic events superimpose their effects on these underlying impacts and accelerate land loss (*high confidence*) (e.g., Hurricanes Katrina and Rita in 2005, Barras *et al.*, 2008). To forestall submergence and frequent flooding, many delta cities now depend on a substantial infrastructure for flood defense and water management (Nicholls *et al.*, 2010).

Deltas are substantially impacted by river floods and oceanic storm surges and tsunamis (*very high confidence*). Tropical cyclones are noteworthy for their damages to deltas, e.g., the Mississippi delta by Hurricane Katrina in 2005 (Barras *et al.*, 2006), the Irrawaddy delta by Cyclone Nargis in 2008, and the Ganges-Brahmaputra delta by Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray *et al.*, 2012)(Box CC-TC). A detailed study of 33 deltas around the world found that 85% of the deltas had experienced severe flooding in the past decade, causing the temporary submergence of 260,000 km^2 (Syvitski *et al.*, 2009).

Projected impacts

The projected natural impacts on deltas under changing global climate are caused mainly by extreme- precipitation induced floods, sea-level rise, and accompanying changes of waves and storm surges. These will result in increased coastal flooding, decreased wetland areas, increased coastal erosion, and increased salinization of cultivated land and groundwater (*high confidence*) (McLeod *et al.*, 2010; Day *et al.*, 2011) (Box CC-TC). The surface area of flooding in 33 deltas around the world is projected to increase by 50% under the future sea-level rise projected for 2100 using the IPCC AR4 scenario (Syvitski *et al.*, 2009). Non-climatic drivers (e.g., reduction in sediment delivery, subsidence, and land-use changes) more than climatic drives have affected deltas for the last 50 years (*very high confidence*) (Syvitski, 2008). Densely populated deltas are particularly vulnerable due to further population growth together with the above-described impacts. The impacts of further sea-level rise beyond 2100 show a more complex and enhanced flood risk on deltas (e.g., Katsman *et al.*, 2011).

In summary, there is *very high confidence* that increased human drivers are the primary cause in changes of deltas (*high agreement, robust evidence*). There is *high agreement* that future climate changes through sea-level rise and increased storminess will exacerbate the problems in deltas with the increase of further human stress.

5.4.3. Human Systems

5.4.3.1. Human Settlements

The most important effects of climate change on coastal settlements include dry land loss due to erosion and submergence, damage of extreme events on built infrastructure (such as wind storms, storm surges, floods, heat extremes and droughts), effects on health, food and water-borne disease, effects on energy use, and effects on water availability and resources (Hunt and Watkiss, 2010). Assessments of climate impacts on settlements have almost exclusively focused on the impacts of sea level rise and coastal flood events. A large number of regional, national and sub-national scale studies have been conducted and Tables 5-4 and 5-5 highlight some of these studies. A comprehensive account of impacts, vulnerabilities and risks in specific regions is given in the Regional Chapters. At the global scale, studies have focused either on exposure to sea-level rise or extreme water levels or on the physical impacts of flooding, submergence and erosion.

[INSERT TABLE 5-5 HERE
Table 5-5: Summary of Coastal Vulnerability Assessments conducted at national or regional scale. Studies that either costed (Adapt$) or considered adaptation options (Adapt) are indicated. In studies that have considered

adaptation: WOA=without adaptation; WA=with adaptation. CVI=Coastal Vulnerability Index; GIS=Geographic Information System, DIVA=Dynamic Interactive Vulnerability Assessment model. RSLR=relative sea level rise.]

Exposure studies confirm the findings of AR4 that coastal vulnerability and risks are strongly influenced by non-climatic drivers. The population exposed to the 1 in 100 year coastal flood is projected to increase from 271 million in 2010 to 345 million in 2050 due to socio-economic development only (UN medium fertility projections) (Jongman *et al.*, 2012). For coastal cities there is *high confidence* that population growth, economic growth and urbanization are the most important drivers of increased exposure (Seto, 2011; Hanson *et al.*, 2011; Chapter 14). For 136 port cities above one million inhabitants the number of people exposed to a 1 in 100 year coastal flood event is expected to increase from 39 million in 2005 to 59 million by 2070 through 0.5 m global mean sea level rise alone and to 148 million if socio-economic development (UN medium population projections) is considered on top of this (Hanson *et al.*, 2011). Asia is expected to continue to have the largest exposed population, North America and Asia the largest economic exposure and North and Sub-Saharan Africa the largest increases in exposure (Dasgupta *et al.*, 2009; Vafeidis *et al.*, 2011; Jongman *et al.*, 2012). As urban population represents increasing proportion of world populations, urban floods will account for an increasing percentage of total flood impact as seen in Pakistan, Australia and Brazil (Jha *et al.*, 2011).

For deltas, another major driver of increases in exposure is relative sea-level rise due to subsidence. 85% of the world's largest deltas have experienced severe flooding in the last decade and the area exposed to flooding could increase by more than 50% by 2100 under current projections of sea-level rise (Syvitski *et al.*, 2009). Under medium UN population projections, human-induced subsidence alone is expected to increase the global economic exposure of 136 major port cities by around 14% although this driver only applies to 36 of the cities (Hanson *et al.*, 2011).

While some literature does not make a clear cut between exposure and impacts (e.g., Dasgupta *et al.*, 2007; Brecht *et al.*, 2012), it is important to distinguish these concepts, as exposure estimates do not consider existing or future adaptation measures that protect the exposed population and assets against coastal risk (Hinkel, 2012). Since AR4, a number of studies, listed in Table 5-5, have provided global assessments of coastal impacts on human settlements including the effects of adaptation. All of these studies also assess monetary costs of impacts and adaptation (5.5.3.). While there is *limited evidence* (few studies and models) three findings emerge.

First, while the global potential impacts of coastal flood damage and land loss on human settlements in the 21st century are substantial, impacts can be reduced substantially through coastal protection (*limited evidence, high agreement*). Nicholls *et al.* (2011) estimated that without protection 72-187 million people would be displaced due to land loss due to submergence and erosion by 2100 assuming sea level increases of 0.5-2.0 m by 2100. Upgrading coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel *et al.* (2012) estimate the number of people flooded annually in 2100 to reach 170-260 million per year in 2100 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, assuming global mean sea-level rises of 0.6-1.3 m by 2100.

Second, despite the delayed response of sea-level rise to global warming levels (WG1, Chapter 3) mitigation may limit 21st century impacts of increased coastal flood damage, dry land loss and wetland loss substantially (*limited evidence, medium agreement*) albeit there is *little agreement* on the exact numbers. Nicholls and Lowe (2004) estimated that stabilizing emission at 550 ppm reduces the annual number of people flooded a factor 50% in 2110 compared to a scenario of unmitigated emissions. Tol (2007) found that stabilizing emissions at 550 ppm reduces global impacts on wetlands and drylands by about 10% in 2100 compared to scenario of unmitigated emissions. Hinkel *et al.* (2012) reported that stabilizing emissions at 450 ppm-CO_2-eq reduces flood risks in 2100 by 23-29%. All three studies only consider the effects of mitigation during the 21st century and due to the thermal expansion component of sea level rise. Mitigation is expected to be more effective when considering impacts beyond 2100 and other components of sea leve rise (WG1 Chapter 13).

Third, studies confirm AR4 findings that there are substantial regional differences in coastal vulnerability and expected impacts (*limited evidence, high agreement*). Most countries in South, South East and East Asia are particularly vulnerable to sea-level rise due to rapid economic growth and coastward migration of people into urban coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated

areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth also increases the capacity to adapt and the benefits of adaptation are also highest in these regions (Nicholls *et al.*, 2010). On the contrary, while many African countries experience a similar trend in rapid urban coastal growth, the level of economic development is generally lower and hence the capacity to adapt is smaller (Hinkel *et al.*, 2011; Kebede and Nicholls, 2012).

Many gaps remain. The available studies have only explored a small fraction of the underlying uncertainty. Only few assessments consider global mean sea-level rise scenarios beyond the range given in AR4, thus excluding the impacts of a possible large contribution of the ice sheets of Greenland and Antarctica to global mean sea-level rise (Sect. 5.3.2, and WG1 Ch. 13). Studies considering regional patterns of climate-induced sea-level rise as well as human-induced subsidence are few. Many studies rely on few or only a single socio-economic scenario. Few studies consider adaptation and those that do generally ignore the wider range of adaptation options beyond hard protection options. Integrated studies assessing multiple hazards, multiple impacts and trade-offs between adaptation options are rare.

_____ START BOX 5-1 HERE _____

Box 5-1. Coastal Megacities

Large coastal urban areas offer both concentrated risk and resources for living with and adapting to the impacts of climate change. When climate related disasters hit megacities costs can be very high: Storm Sandy is estimated to have resulted in more than US$100 billion of damages for New York and its hinterland. When impacts reach these levels, and when strategic infrastructure is damaged, losses in large cities are capable of impacting on regional and global economies through the disruption of globalized flows of goods, resources and capital. Large-scale coastal urbanization is most concentrated in south and southeast Asia. Asia is also a world region with high exposure to climate and weather related hazards and the potential for these to be compounded by geophysical hazards, and those more directly caused by human action such as subsidence.

Of 21 megacities worldwide defined by having populations in excess of 10 million, 14 are in the coastal zone – within 100km and 50m elevation from the coast (Figure 5-4) and it is anticipated that the number of coastal megacities will continue to grow, especially in Africa and Asia. Growth will be largely through planned development but may also feature of unplanned, spontaneous and often illegal development – with implications for the limits and scope of adaptive capacity and management. Growth in neighbouring urban regions offers the prospect of mega-cities or mega-urban-regions, currently the largest is the Hong Kong-Shenhzen-Guangzhou region in China, with a population of 120 million. Many other large coastal cities (e.g., Cairo, London and Sao Paulo) offer important lessons on planning and risk management at scales that indicate the importance of a flexible approach to the study of coastal mega-urbanization.

[INSERT FIGURE 5-4 HERE
Figure 5-4: Mega-urbanisation of on the coast. Source**:** Blackburn S and Marques da Silva C (2013) Mega-urbanisation on the coast: Global context and key trends in the twenty-first century, in Pelling M and Blackburn S (eds) Megacities and the Coast: Risk, Resilience and Transformation, Earthscan: London.]

Contemporary approaches to risk management acknowledge the need for soft risk reduction measures such as education, good governance, and risk communication, being applied in conjunction with hard engineering solutions such as sea walls, groynes and levees and green-engineered equivalents. However applying these principles in megacities is challenging, requiring collaboration between a multitude of stakeholders. These include actors operating at all scales from the international (in the case of large land-owning corporations and supranational donors) to the individual. Good governance is key to risk management, but there is much debate over precisely what this entails and its limitations.

The prospect of dangerous climate change bringing increasing rates of sea-level rise and coastal storminess by mid century asks serious questions of urban planners today. This is especially so in places where these hazard drivers are exacerbated by local conditions, for example of subsidence. Middle-income countries experiencing the most rapid mega-urban expansion also possess an opportunity to plan now for potential risk mid-century and beyond. It is more

difficult still to confront the challenge of retrofitting or redesigning cities where current land-use will configure future risk. The next decade is likely to be critical for realigning urban planning, reaching out to informal and regulating market-led developments. Responding to dangerous climate change requires joined-up risk management that can consider transformational adaptation with considerable local impacts on the way cities are imagined, governed and shaped, alongside contemporary, incremental adaptation options.

_____ END BOX 5-1 HERE _____

5.4.3.2. Industry, Infrastructure, Transport, and Network Industries

There is *high confidence* that coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water and sewerage are sensitive to a range of extreme weather and climate events (Handmer *et al.* 2012) and many of these are projected to change over the coming decades (Seneviratne *et al.*, 2012). This is especially relevant considering the fact that most industrial facilities, infrastructure and networks are designed for life cycles extending over several decades, even extending well into the twenty-second horizon such as new nuclear power plants (Wilby *et al.* 2011).

Table 5-6 summarizes potential impacts of sea level rise, coastal floods and storms on critical coastal infrastructure in the communications, energy, transportation and water waste sectors.

[INSERT TABLE 5-6 HERE
Table 5-6: Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig (2010), Zimmerman and Faris (2010).]

Severe storms with associated winds, waves, rain, lightning and storm surges are particularly disruptive to transport and power and water supplies. In such network configurations, flooding of even the smallest component of an intermodal system can result in a much larger system disruption. For instance, even though a transportation terminal may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation (CCSP, 2008). Sea transport accounts for more than 80% of global goods trade (by volume) and so disruption to port activities in one location can disrupt supply chains, which can have far reaching consequences (Handmer *et al.*, 2012).

Some low-lying railroads, tunnels, ports and roads are already vulnerable to flooding and rising sea levels (5.3.3.2) will exacerbate the situation by causing more frequent and more serious disruption of transportation services under extreme sea levels unless adaptation is enforced. Furthermore, sea-level rise will reduce the extreme flood return periods and will lower the design critical elevations of infrastructure such as airports, tunnels, coastal protections and ship terminals (Jacob *et al.*, 2007). Coastal infrastructural instability may result from natural hazards triggered by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be exacerbated by earthquake liquefaction if GWL increases with sea-level rise (Yasuhara *et al.*, 2007). Other impacts may arise in coastal industries in high latitudes affected by permafrost thaw causing ground stability and erosion thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce *et al.*, 2010).

There is *high confidence* that climate impacts on coastal industries vary considerably depending on geographical location, associated weather and climate and specific composition of industries within particular coastal regions.

While there is *robust evidence* of the impacts and consequences of extreme events on coastal infrastructure and industrial facilities there are limited assessments on projected impacts. For example, it is estimated that a hypothetical 1 m rise in relative sea level projected for the Gulf Coast region between Alabama and Houston over the next 50-100 years would permanently flood a third of the region's roads as well as putting more than 70% of the regions ports at risk (CCSP, 2008).

Although not completely coastal, the estimated costs of climate change to Alaska's public infrastructure could add US$3.6-6.1 billion (+10% to 20% above normal wear and tear) from now to 2030 and US$5.6-7.6 billion (+10% to 12%) from now to 2080 (Larsen *et al.*, 2008). Higher costs of climate change for coastal infrastructure are expected due to its proximity to the marine environment. Other projected impacts are beneficial for the transportation system. For example, decline of Arctic sea-ice coverage could extend seasonal accessibility to high-latitude shipping routes such as the northwest shipping route that connects the Atlantic to the North Pacific (MCCIP, 2008).

Hanson *et al.* (2011) presents a first estimate of the exposure of the world's large port cities to coastal flooding due to sea-level rise and storm surge in the 2070s. The analysis suggests that the total value of assets exposed in 2005 across all cities considered is estimated to be US$3,000 billion; corresponding to around 5% of global GDP in 2005. By the 2070s, and assuming a homogeneous global sea level rise of 0.5 m, increased extreme water levels up to a 10% and a fixed subsidence rate in susceptible cities with respects today values, asset exposure is estomated to increase to approximately 9% of projected global GDP in this period.

5.4.3.3. Fisheries, Aquaculture, and Agriculture

The coastal zone supports significant fisheries, aquaculture and agricultural activities. Fisheries and aquaculture globally employ 43.5 million people (Daw *et al.*, 2009) and contribute for more than 20% to the dietary animal protein of nearly 1.5 billion people (FAO, 2010). Rice production, the world's number one food crop, is a major crop grown in the low-lying deltaic regions of Asia (Wassman *et al.*, 2009).

Observed impacts

Climate variability and change impact both fishermen livelihoods (Badjeck *et al.*, 2010) and fish production (Barange and Perry, 2009). In the North Sea, ocean warming over the period 1977-2002 led to 8 times more fish species (Hiddink and Hofstede, 2008). In southeastern Australia, Last *et al.* (2011) found an increasing abundance of 45 fish species of warm temperate origin (Ridgeway, 2007), a decline abundance for 9 species, and predicted the potential for longer term detrimental effects for cool temperate species endemic to the region. Impacts of climate change on aquaculture (*Mytilus edulis and Salmo salar*) in the UK and Ireland have been difficult to discern from natural environmental variability (Callaway *et al.*, 2009).

The impact of sea surface temperature changes on fisheries yields over the last 25 years is negative for the Northeast Atlantic large marine ecosystems, and positive for the Indian Ocean (Sherman *et al.*, 2009). In coastal Louisiana, saltwater intrusion was found to reduce the population size of the freshwater western mosquitofish (*Gambusia affinis*) (Purcell *et al.*, 2010). Eutrophication and hypoxia give rise to frequency and intensity of harmful algal blooms (MEA, 2005). A combination of factors renders the Pacific coast and coastal estuaries particularly vulnerable to acidified water (Newton *et al.*, 2010).

The combination of rice yield reduction induced by climate change and inundation of lands by seawater causes an important reduction in production (Chen *et al.*, 2012). Seawater inundation has become a major problem for traditional agriculture in Bangladesh (Rahman *et al.*, 2011), and in low-lying island nations (e.g. Lata and Nunn, 2012).

Projected impacts

Fisheries may be impacted either negatively or positively (Cinner *et al.*, 2012; Meynecke and Lee, 2011; Hare *et al.*, 2010) depending on the latitude, location and climatic factor. Using a partial-equilibrium analysis, Narita *et al.* (2012) estimated that the global economic costs of production loss of mollusks due to ocean acidification by the year 2100 could be over 100 billion USD. Warming ocean temperatures can lead to the migration of the sea urchin (*Centrostephanus rodgersii– Diadematidae*) in Australia (Ling *et al.*, 2009). For aquaculture, negative impacts of

rising ocean temperatures will be felt in the temperate regions whereas positive impacts will be felt in the tropical and subtropical regions (De Silva and Soto, 2009).

In summary, there is *medium confidence* that changes have occurred to the distribution of fish species with evidence of poleward expansion of temperate species (*high agreement, limited evidence*). There *is limited evidence* to suggest that tropical and subtropical aquaculture has not been adversely affected by rising ocean temperatures to date. There is also *medium confidence* that coastal agriculture has experienced negative impacts due mainly to increased frequency of submersion of agricultural land by saltwater inundation (*high agreement, limited evidence).*

5.4.3.4. Coastal Tourism and Recreation

Coastal tourism is the largest component of the global tourism industry. More than 60% of Europeans opt for beach holidays and beach tourism provides more than 80% of US tourism receipts (UNEP, 2009). More than 100 countries benefit from the recreational value provided by their coral reefs which contributed US$11.5 billion to global tourism (Burke *et al.*, 2011).

Observed impacts

Observed significant impacts on coastal tourism have occurred from changes in extreme events (e.g. flooding, tropical storms, storm surges, heat waves) and climate variability (e.g. drought and prevailing winds accelerating coastal erosion) which can cause damage to infrastructure and tourist attractions (Scott *et al.*, 2008; Bender *et al.*, 2010; Knutson *et al.*, 2010). Observed climate change impacts on the Great Barrier Reef include the coral bleaching episodes in 1998 and 2002 due to higher summer sea temperatures, more severe storms, rising sea levels and coastal erosion although tourists show a low level of climate change concern with respect to coral bleaching (Zeppel, 2012).

Projected impacts

In order to provide some idea of climate change impacts on coastal destinations, many studies have been made on projecting tourism demand, for example, in Europe (Perch-Nielson *et al.*, 2010), East Anglia, UK (Coombes *et al.*, 2009), the Baltic region (Haller *et al.*, 2011) and beach tourism in the Mediterranean (Moreno and Amelung, 2009a) and in 51 countries worldwide (Perch-Nielson, 2010). The studies provide varying details but it is difficult to draw overarching conclusions on tourism demand for coastal destinations. Less is known about the relationship between the impacts of climate change and specific tourist behaviour, activities or flows to coastal destinations (Moreno and Amelung, 2009b) (see Chapter 10). Usually tourists do not consider climate variability or climate change in their holidays *et al.* although there are a few studies to show on the contrary (Alvarez-Diaz *et al.*, 2010; Cambers, 2009).

As for future impacts on coastal tourism, there is *high confidence* in the impacts of extreme events and sea level rise aggravating coastal erosion. A scenario of 1 m sea level rise would be a potential risk to 906 major coastal resort properties in 19 countries in the Caribbean (Scott *et al.*, 2012). The presence of coastal tourism infrastructure will continue to exacerbate beach reduction and coastal ecosystems squeeze under rising sea levels, as exemplified in Martinique (Schleupner, 2008). Carbonate reef structures would degrade under a scenario of at least 2^{o}C by 2050 to 2100 with serious consequences for tourism destinations in Australia, Caribbean and other small island nations (Hoegh-Gulberg *et al.*, 2007). Ocean acidification would add its toll to coral reefs (Box CC-CR).

The costs of future climate change impacts on coastal tourism are enormous. For example, in the Caribbean region, a hypothetical 1-m sea-level rise would result in the loss or damage of 21 CARICOM airports, inundation of land surrounding 35 ports, and at least 149 multi-million dollar tourism resorts damaged or lost from erosion to the coastal beach areas.(Simpson *et al.*, 2011).

In summary, while coastal tourism can be related to climate change impacts, it is more difficult to relate tourism demand directly to climate change. Coastal tourism continues to be highly vulnerable to weather and climate

extremes and rising sea levels with the additional sensitivity to ocean temperature and acidity for the sectors that rely on reef tourism *(high confidence*). Developing countries and small island states within the tropics relying on coastal tourism, are most vulnerable to present and future weather and climate extremes, future sea level rise and the added impacts of coral bleaching and ocean acidification **(***very high confidence*).

5.4.3.5. Health

The relationship between health of coastal populations and climate change include direct linkages (e.g. floods, droughts, storm surges and extreme temperatures) and indirect linkages (e.g. changes in the transmission of vector, food and water borne infectious diseases and increased salinisation of coastal land that affects food production and freshwater supply). Coastal settlements, and in particular informal settlements, concentrate the risks of injury and death due to the risk of storm surges and flooding from rainfall and storm surge (Handmer et al, 2012). This section deals with human health in the context of the coastal zone, while Chapter 11 addresses general health issues and Chapter 6 deals with health issues associated with ocean changes. Understanding the relationship between climate and health is often confounded by socio-economic factors that influence coastal settlement patterns and the level and organisation of the response of authorities to health related issues (Baulcomb, 2011).

Mortality risk in coastal areas is related to exposure and vulnerability of coastal populations to climate hazards. Recent modeling of trends in these components highlights that mortality risk is highest in countries with low GDP and weak governance. A regional analysis of changes in exposure, vulnerability and risk indicates that although exposure to flood and cyclone hazards has increased since 1980, the risk of mortality has generally fallen. The reductions reflect strengthening of countries' capacity to respond to disasters (Box 5-1). However, mortality is still rising in the countries with the weakest risk governance capacities (UNISDR, 2011).

Coastal regions face a range of diseases that are sensitive to climate. Increased saline intrusion of coastal land through rising sea levels and changes to river flow is linked to increased incidence of hypertension disease (Vineas et al, 2011). For example, in Bangladesh, higher rates of maternal hypertension disorders have been identified in pregnant women living in coastal regions compared to further inland (Khan et al, 2008). Increasing temperature, humidity and rainfall can increase suitable mosquito habitats, shorten the breeding cycles and reduce the time to infection by vector-borne diseases such as malaria, dengue, leishmaniasis and chikungunya. (Stratten *et al.*, 2008; van Kleef *et al.*, 2010; Pialoux et al, 2007, Kolivras, 2010) and infectious diseases such as diarrhoea, infectious gastrointestinal disease, rotovirus and salmonella (e.g. Chou *et al.*, 2011, Hashizume *et al.*, 2007; 2008a Zhang *et al.*, 2007, 2010; Onozuka *et al.*, 2010). The parasitic disease, Schistosomiasis, is endemic in many tropical and small island coastal regions (Chapter 29) and infection rates have been found to increase linearly with temperature to 30°C but reduce beyond 35°C, because of increased mortality in the snail intermediate host. (Mangal *et al.* 2008).

Cholera outbreaks are also linked to rainfall, patterns and other seasonal climate patterns (e.g. Hashizume et al, 2008b, 2010) and variations in SST (e.g. Koelle et al, 2005). Outbreaks of toxins generated by Harmful Algal Blooms (HABs) such as ciguatera have been linked to SST variability (e.g. Jaykus *et al.*, 2008; Erdner *et al.*, 2011). However, in general there is *limited evidence* and *low confidence* in how global climate change will impact HABs (Chapter 6). The potential impacts of HABs in human health and different ecosystem services suggests increased monitoring of significant range extensions and associated increases in biotoxins is necessary (Hallegraeff, 2010). Nontoxic blooms that grow to high biomass also can have detrimental effects on biodiversity through oxygen depletion and physical shading of the benthos (Erdner *et al.*, 2011) with consequences for ecosystem health, human nutrition and health.

Under future climate conditions, expansion of brackish and saline water bodies in coastal areas under projected sea level rise may increase the incidence of associated vector-borne diseases (Ramasamy and Surendran, 2011) and salinity-related diseases such as diarrhea and hypertension (Vineas et al, 2011). Human responses to climate change also may also influence outcomes on health. However, sparsity of empirical climate-health data increases uncertainties around such projections (Kolstad and Johansson (2011).

Evidence continues to emerge of relationships between many diseases that affect human health in the coastal zone and climate including changes in air and water temperature, rainfall and humidity, coastal salinity and increased salinisation of coastal land. However, the relationships are often complex and vary between diseases and even regionally for the same disease. The interplay between climate and human systems with regards to health impacts is poorly understood and this continues to confound reliable projections of health impacts. (*high agreement, robust evidence*).

5.4.4. Summary: Detection and Attribution

Coastal systems, consisting of natural and human systems, have been heavily influenced by human activities including those associated with climate changes (*high agreement, robust evidence*).

Coastal ecosystems such as rocky shores and coral reefs show the most evidence of the impacts of climate change (5.4.2.2, 5.4.2.4), the most prominent effects being the range shifts of species in response to ocean warming (*high confidence*), changes in biodiversity (*high confidence*) in relation to ocean warming and acidification, and mass coral bleaching and mortality in response to ocean warming (*very high confidence*). Decreased calcification in many reef-building corals and coralline algae is reported widely (*high confidence*), however its attribution to either warming or acidification has proven difficult (*medium confidence*)(5.4.2.4). Ocean warming is also leading to range shifts in mangrove forests and seagrass meadows (*medium confidence*)(5.4.2.3). Seagrass meadows are already under stress due to ocean warming (*high confidence*), and in particular heat waves, which lead to widespread seagrass mortality (*high confidence*). Kelp forests have been reported to decline in temperate areas in both hemispheres, attributed to ocean warming (*high confidence*)(5.4.2.3). The spread of subtropical invasive macroalgal species is believed to be facilitated by climate change, adding to the stresses temperate seagrass meadows experience from ocean warming (*medium evidence, high agreement*)(5.4.2.3). The changes of the distribution of fish species with evidence of poleward expansion of temperate species have occurred (*medium confidence*)(5.4.3.3). There *is limited evidence* to suggest that tropical and subtropical aquaculture has been adversely affected by rising ocean temperatures to date (5.4.3.3).

Though the range shift of mangroves is recognized, mangrove forests and seagrass meadows are declining globally (*very high confidence*) mainly due to land-use changes and coastal erosion (5.4.2.3). Widespread erosion of beaches and dunes has been observed over the past century or more (*robust evidence*) (*very high confidence*). However attributing shoreline changes to climate change is difficult due to the multiple natural and anthropogenic drivers contributing to coastal erosion (*low confidence*) (5.4.2.1). There is *very high confidence* that increased usage of groundwater resources for agriculture and coastal settlements globally has led to a reduction in groundwater quality, including increased salinization (*high agreement, robust evidence*), however, attribution to climate change is *low* (5.4.2.5), human drivers being the primary cause in these changes and degradation of highly-populated deltas and lowlands around estuaries and lagoons (*high agreement, robust evidence*)(5.4.2.7).

Exposure studies confirm the findings of AR4 that coastal vulnerability and risks are strongly influenced by non-climatic drivers. Population of people living in coastal lowlands is increasing and more than 270 million people in 2010 are already exposed to flooding by the 1 in 100 year coastal flood (5.4.3.1)(*very high confidence*). Population growth and land subsidence in coastal lowlands are the major cause and there is *very low attribution* to climate changes. The interplay between climate and human systems with regards to health impacts is poorly understood (*high agreement, robust evidence*)(5.4.3.5).

The coastal systems are affected by both climate-related and human drivers, and complex interactions of both. Though there is *high* attribution to climate changes as coral bleaching and species shift, most of causes in other changes to the coastal system are attributed to mainly human activities (human drivers). Further analysis will be required to more clearly discriminate the relative contributions from human and climate-related drivers.

[INSERT FIGURE 5-5 HERE
Figure 5-5: Summary of detection and attribution in coastal areas.]

5.5. Adaptation and Managing Risks

This section assesses the literature on available on approaches for appraising and implementing coastal adaptation (5.5.1), adaptation options (5.5.2), costs and benefits of coastal adaptation (5.5.3), observed coastal adaptation practice (5.5.4), observed barriers to coastal adaptation (5.5.5), and finally linkages between coastal adaptation and mitigation (5.5.6).

5.5.1. Framing and Approaches

5.5.1.1. Overview of Approaches

Adaptation in general and coastal adaptation in particular are broad concepts referring to a wide range of human activities related to the process of framing the adaptation issue, assessing adaptation (i.e., identifying and analyzing adaptation options), implementing options and monitoring and evaluating these (e.g., UKCIP, 2003; PROVIA, 2013). As a result, a wide variety of approaches are applied (Chapters 2, 15, 16 and 17 for a comprehensive account).

For coastal adaptation, the literature on approaches falls into three categories: decision-analytical approaches, approaches of institutional and governance analysis and practical approaches that cover all stages of the adaptation process.

5.5.1.2. Decision Analysis

Decision-analytical (DA) approaches analyse a particular decision using formal methods in order to identify preferable actions from a set of alternative actions (also called options, alternatives or strategies) given some evaluation criteria. This section highlights some paradigmatic applications of DA methods to coastal adaptation; for a compressive treatment see Chapter 2 (Foundations for decision-making) and Chapter 17 (Economics of Adaptation).

Many standard methods for decision-making under uncertainty use the criterion of optimality (e.g., optimum utility, optimal cost-benefit ratio, etc). These methods cannot be applied for long-term adaptation decisions as they require the computation of expected utility or expected benefits, which is not possible in principle (Lempert and Schlesinger, 2001; Hinkel and Bisaro, 2013). As many coastal decisions involve options with investment time scales of 30 to over 100 years (e.g., land-use planning, flood defenses, construction of housing and transportation infrastructure; see 5.5.2), DA approaches beyond optimization are required (Hallegate, 2009).

Robust decision-making (RDM) refers to a range of alternative approaches that replace the evaluation criterion of optimality with the criterion of robustness. Uncertainty is not represented through a single probability distribution but through a range of alternative scenarios and robust strategies that work well over a wide range of these scenarios are preferred (Lempert and Schlesinger, 2000; Lempert and Collins, 2007). Application of RDM to Port of Los Angeles infrastructure is one of the few applications to coastal adaptation (Lempert *et al.* (2012).

Another set of approaches uses the criterion of flexibility to decide between alternative strategies. Flexible and reversible options are favored over non-flexible and non-reversible ones and decisions are delayed to keep future options open (Hallegate, 2009).

The adaptation pathways approach implements the criterion of flexibility by characterizing alternative strategies in terms of two attributes: i) adaptation tipping points (ATP), which are points beyond which strategies are no longer effective (Kwadijk *et al.*, 2010), and ii) what alternative strategies are available once a tipping point has been reached (Haasnoot *et al.*, 2012). Importantly, the exact time when an ATP is reached does not matter; it is rather the flexibility of having alternative strategies available that is driving the decision. Prominent applications of this

approach include the Thames Estuary 2100 Plan (Low *et al.*, 2009; Penning-Roswell *et al.* 2011; Box 5-2), the Dutch Delta Programme (Kabat *et al.*, 2009; Box 5-3) and the New York City Panel on Climate Change (Rosenzweig *et al.*, 2011).

These and other approaches may also be embedded into multi-criteria-analysis (MCA), which considers multiple criteria that may include robustness and flexibility. The application of MCA to coastal decisions is wide spread. Another response to the deep uncertainty characterizing future climate drives is adaptive management, which is the idea of practicing adaptation and evaluating outcomes *ext-post* instead of analyzing decisions *ex-ante*; (e.g. practical approaches in 5.5.2.4).

5.5.1.3. Institutional and Governance Analysis

Institutional and governance analysis (IA) comprise a variety of approaches that aim at describing and explaining the emergence and performance of institutions and governance structures (GS) (Hinkel and Bisaro, 2013). IA is particularly relevant to coastal adaptation, because deciding between options and implementing them is an ongoing process involving complex inter-linkages between public and private decisions at multiple levels of decision making and in the context of other issues, existing policies, conflicting interests and diverse GS (e.g, Few *et al.*, 2007; Urwin and Jordan, 2008; Hinkel *et al.*, 2009). The non-consideration of this context may hinder or mislead adaptation decisions and implementations (5.5.5). IA strives to understand this context and insights gained may be employed to craft effective institutions and policies for adaptation.

For coastal adaptation, there is *high confidence* that the effectiveness of existing GS is hindered due to a lack of horizontal and vertical integration of organizations and policies. Weak vertical administrative interplay in Sweden (Storbjörk and Hedren (2011)); poor integration in higher-level governance and limited effectiveness of institutional arrangements of Coastal Partnership in UK (Stojanovic and Barker, 2008); difficulty to translate national level recommendations into local level actions in the UK (Few *et al.*, 2007); coastal policies with ambigous or contradictory goals (Bagstadt *et al.*, 2007) and fragmented economic incentivices in the US (Seto, 2011) or coastal policies not taken into account longer-term climate change in a number of African cases (Bunce *et al.*, 2010) are a few examples.

There is *medium evidence* that governance issues are particularly challenging when considering planned retreat. While managed realignment is on the political agenda in Germany and the UK, the political costs of doing so are high as both the existing GS as well as public opinion are geared towards protection, so that short election cycles do not provide incentives for politicians to undertake actions that may produce benefits in the long term (Few *et al.*, 2007; Rupp-Armstrong and Nicholls, 2007). Along the coast of South East Queensland, Australia, the option of planned retreat is disappearing because of rapid coastal development favored by liability laws. To prevent this, risks and responsibilities would need to be redistributed from governments to beneficiaries of development (Abel *et al.*, 2011).

While there is *high confidence* that many institutional factors are decisive in enabling coastal adaptation, the role of coastal institutions in adaptation is generally under-researched. Contextually differentiated institutional analysis considering both biophysical and social system characteristics (Dietz *et al.*, 2003; Ostrom, 2009) as found in the fields of socio-ecological systems (Folke *et al.*, 2005; Ostrom 2007, 2009) and new institutional economics (Hagedorn *et al.*, 2002; Bougherara *et al.*, 2009; Ostrom, 2005, Geels, 2011) are practically non-existent. Most work focuses on Australia, US, Germany and the UK with little work on developing countries.

5.5.1.4. Approaches to Adaptation Practice

Generally, approaches to adaptation practice build on already existing policy and practice frameworks and cover the whole adaptation processes from framing the issue and analyzing options to implementing adaptation actions and monitoring and evaluation.

Integrated Coastal Zone Management (ICZM) is a long-term, institutionalized and iterative process that promotes the integration of coastal activities of relevant policy makers, practitioners and scientist across coastal sectors, space and organizations with a view to use coastal resources in a sustainable way (Hiledebrand and Norrena, 1992; Sorenses 1993; Sterr *et al.*, 2003; Sales, 2009; Christie *et al.*, 2005; WG2 Glossary). Considering climate change in this framework does not mean radical changes to ICZM, because ICZM already emphasizes the integration of coastal issues across sectors and policy domains as well as the long-term perspective (e.g., Hofstede, 2008; Falaleeva *et al.*, 2011), but there is need to extend decision making horizons (Tobey *et al.* 2010).

So far, however, there is *limited evidence* of the effectiveness of ICZM combined with climate change adaptation. ICZM itself has been applied throughout the world for over 40 years and while demonstrable befits are reported (e.g., Stojanovic and Ballinger, 2009) many obstacles to its successful implementation still remain (*high confidence*). A recent review of ICZM in Europe concluded that the complexity of coastal regulations, demographic deficits, lack of sustainable finance and a failure to involve communities, business and industry hinder its implementation (Shipman and Stojanovic, 2007). Developing countries also struggle to meet the goals of ICZM due to many factors (Box 5-4).

Another prominent framework used for coastal adaptation practice is adaptive management (AM), which has been developed as a response to the deep uncertainty characterizing ecosystem management, where it is often impossible to predict outcomes of management interventions (Holling, 1968; Walters, 1986). There are numerous applications of AM to coastal management (e.g., Walters, 1997; Marchand, 2011, Mulder *et al.*, 2011), but as the majority of these are very recent, there is *limited evidence* of its long-term effectiveness. Limitations of AM are also apparent such as the potential high cost of experimentation and and a range of institutional barriers hindering the delivery of flexible management approaches (e.g. Gunderson *et al.*, 1995, McLain and Lee, 1996; Johnson 1999).

Community-based adaptation (CBA) refers to the generation and implementation of locally-driven adaptation strategies that address both climate change impacts and development deficits for the climate vulnerable poor and strengthen the adaptive capacity of local people to climate and non-climate risk factors (Reid *et al.*, 2009; Nicholls *et al.*, 2007; Ayers and Dodman, 2010; Ayers and Huq, 2013; WG2 AR5 Chapter 14, 14.2.1; Chapter 15, 15.4.3.1; Chapter 24, 24.4.6.5). CBA approaches have been developed through active participatory processes with local stakeholders (Ayers and Forsyth, 2009), and operating on a learning-by-doing, bottom up, empowerment paradigm (Huq and Reid, 2007; Kates, 2000). CBA experiences emphasize that it is import to understand a community's unique perceptions of their adaptive capacities in order to identify useful solutions (Parvin *et al.*, 2008; Paul and Routray, 2010; Badjeck et al, 2009) and that scientific and technical information on anticipated coastal climate impacts needs to be translated into a suitable language and format that allows people to be able to participate in adaptation planning (Saroar and Routray, 2010). Further, effective CBA needs to consider measures that cut across sectors and technological, social and institutional processes; technology by itself is only one component of successful adaptation. (Sovacool *et al.*, 2011; Rawlani and Sovacool, 2011; Pelling, 2011; Gibbs, 2009).

Other important policy and practice frameworks in place in the coastal zone include poverty reduction, development and Disaster Risk Reduction (Romieu *et al.*, 2010; Mercer, 2010; Mitchell *et al.*, 2010; Polack, 2010; Gero *et al.*, 2011; Kirshen *et al.*, 2011; Halpern *et al.*, 2008b)

Across these and other approaches there is *high agreement* on the following three principles. One, information on efficient adaptation options alone (as assessed through DA approaches) may not fully serve managers need and requires to be supplemented by financial and technical assistance as well as boundary organizations which serve as an interface between science and practice (Tribbia and Moser, 2008). Two, the adaptation and decision making processes should be participatory and inclusive, integrating all relevant stakeholders (Dolan and Walker, 2004; O'Riordan and Ward, 1997; Milligan *et al.*, 2009). Three, the adaptation processes must be set up to foster mutual learning, experimentation and deliberation amongst stakeholder and researchers (Fazey *et al.*, 2010; Kenter *et al.*, 2011). Neither scientific climate knowledge alone nor indigenous knowledge alone is sufficient (Sales, 2009; Dodman and Mitland, 2011; Bormann et al, 2012). Coastal adaptation is increasingly acknowledged to be a "wicked problem" (Rittel and Webber, 1973), in the sense that there is often no clear agreement about what exactly the adaptation problem is and there is uncertainty and ambiguity as to how improvements might be made (Moser *et al.*

2012). As coastal systems are complex, diverse and dynamic, their governance needs experimentation and learning by doing (Jentoft, 2006).

While there is *high agreement* on these principles, there is little systematic review and hence *limited evidence* on why a given approach is effective in a given context (and not in another). The need for systematic evaluation and institutional research targeted at a differentiated understanding of these approaches is high. Furthermore, despite experimentation with these approaches, meeting the multiple goals, improving governance, accounting for the most vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely aspirational. Meanwhile development in high risk areas grows, coastal ecosystems continue to degrade in many regions, coastal freshwater resources are being overdrawn in many highly populated areas, and vulnerability to coastal disasters grow (e.g., Jentoft, 2009; McFadden, 2008; Mercer, 2010; Shipman and Stojanovic, 2007).

5.5.2. Adaptation Options

Selecting appropriate adaptation options can be challenging considering the ample range of options available. A detailed discussion on general adaptation needs and options can be found in (chapter 16). As a first approximation, adaptation options were classified into: institutional and social options (14.3.2.1), technological and engineered options (14.3.2.2) and ecosystem-based adaptation options (14.3.2.3). In terms of coastal adaptation, most of the existing options can be included within this classification.

The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation and protection (Nicholls *et al.*, 2007) is now widely used and applied in both developed and developing countries (Boateng, 2010; Linham and Nicholls, 2012). This trilogy of strategies has also been translated as retreat, defend or attack (Peel, 2010). Protection aims at advancing or holding existing defence lines by different options such as: land claim, beach and dune nourishment, the construction of artificial dunes, hard structures such as sea walls, sea dikes and storm surge barriers or removing invasive and restore native species. Accommodation is achieved, increasing flexibility, by flood proofing, flood agriculture, flood hazard mapping, the implementation of flood warning systems or replacing armoured by living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline setbacks and managed realignment, for example, by breaching coastal defences allowing the creation of an intertidal habitat.

Since AR4 coastal adaptation options have been revised and summarized in several guidebooks (USAID, 2009; EPA, 2009; UNEP, 2010). Especially relevant has been the growth of Community Based Adaptation options. Table 5-7 compiles different examples, of options implemented to address climate change impacts in coastal areas.

[INSERT TABLE 5-7 HERE
Table 5-7: Community-based adaptation options.]

5.5.3. Global Adaptation Costs and Benefits

Since AR4, only a few studies have been published that provide comprehensive and internally consistent estimates of the costs of sea-level rise and adaptation at global scales. These relying either on the FUND (Anthoff *et al.*, 2010; Nicholls and Tol, 2009) or the DIVA model (Hinkel and Klein, 2009) and are listed in Table 5-5 and discussed here.

Generally, cost estimates are difficult to compare across studies due to differences in scenarios used, impacts and adaptation options considered, methodologies applied and baseline conditions assumed. No study covers all of the major sea-level rise impacts as reported in Table 5-4. All of these studies use the direct cost method, in which exogenous prices for adaptation options and damages are taken from data of the respective markets. For wetland loss, direct costs are used too but the “prices” are taken from monetary valuation studies for non-market goods and services (Woodward and Wui, 2001; Brander *et al.*, 2006; Barbier, 2012). Some studies use computable general equilibrium models and growth models to study the indirect and dynamic costs of climate change, including sea level rise. These studies are reviewed in Chapter 10.

There is *high agreement* that the cost of sea-level rise (sum of adaptation and residual damage cost) are smaller with coastal protection than without for the 21st century and the global scale, when considering the impacts of increased coastal flood damage and land loss due to erosion. (Nicholls and Tol, 2006; Anthoff *et al.*, 2010; Hinkel *et al.*, 2012). *Evidence is low*, however, as only a few studies are available. Considering dryland and wetland loss only, the FUND model shows that under a GMSLR of 20-40cm per century it would be economically justified to protect 80% of the exposed coast in all but 15 countries (Nicholls and Tol, 2006) and even under an extreme GMSLR of 6m per century 50% of today's coastline would still be worth protecting (Nicholls *et al.*, 2008). Considering flood damage only, an application of DIVA shows that for 21st century global mean SEA LEVEL RISE scenarios of 60-126cm, upgraded protection through dikes (levees) may reduce total costs by factors 3 to 5 as compared to no upgrades in protection (Hinkel *et al.*, 2012).

There is also *high agreement* that costs and benefits of sea-level rise impacts and adaptation vary strongly between regions and countries and that some developing countries and Small Island States may reach their limits of adaptive capacity or may not be able to bear the costs of impacts and adaptation without external support (Chapter 29, 29.6.2.1). Even with protection, the cost of land loss due to submergence are projected to be above 1% of national GDP for Micronesia, Palau, the Bahamas and Mozambique under 1m of sea level rise (Anthoff *et al.*, 2010). For coastal flooding, annual damage and protection cost are projected to lie between 5% and 9% of national GDP for Kiribati, the Solomon Islands, Vanuatu and Tuvalu in 2100 under 64 cm of global mean sea-level rise (Hinkel *et al.*, 2012). Further substantial costs arise particularly for developing countries due to their current adaptation deficit (i.e. coastal defenses are not adapted to the current climate variability), which is not well understood and requires further analysis (Parry *et al.*, 2009). For example, the adaption deficit of Africa with regards to coastal flooding is estimated to US $300 billion (1995 prices; Hinkel *et al.*, 2011) and that of Bangladesh with respect to cyclones to US$ 25 billion (2009 prices; World Bank, 2011).

Several methodological issues and gaps remain. As there are so few studies of the costs and befits of sea-leverl rise at a global level, *evidence is low*. Uncertainties are largely unknown and the need for further research is large. Impacts considered and damages and losses valued are incomplete. For example, costs of salinity intrusion, land loss due to increased coastal erosion, the backwater effect and the impact of sea-level rise in combination with other drivers on ecosystems have not been assessed at global scales (see Table 5-4). Generally for sea-level rise impacts, it is difficult to establish a “no adaptation” baseline and the choice of the baseline changes damage costs (Yohe *et al.*, 2011).

Furthermore, assessments have focused on protection via hard structures but many more adaptation options are available including, “soft” protection, retreat and accommodation options (Klein *et al.*, 2001; Sect. 5.1) and future work needs to consider these. While the costs of “soft” protection options are largely unknown (Linham and Nicholls 2010), these may provide additional benefits. For example, ecosystem-based adaptation options, also preserve and restore coastal ecosystems whilst protecting against impacts (Espinosa-Romero *et al.*, 2011; McGinnis and McGinnis, 2011; Pérez *et al.*, 2010; Anthony *et al.*, 2009; Alongi, 2008; Zeitlin *et al.*, 2012; Vignola *et al.*, 2009; IUCN, 2008). Finally, it must be noted that protection also further attracts people and development to the floodplain, which together with protection levels leads to ever increasing residual risks with potential catastrophic consequence in the case of defense failure. This is particularly true for many coastal cities such as London, Tokyo, Shanghai, Hamburg and Rotterdam that already rely heavily on coastal defenses (Nicholls *et al.*, 2007).

[INSERT TABLE 5-8 HERE
Table 5-8: Global assessments of costs of sea-level rise.]

5.5.4. Adaptation Practice

Observed adaptation practice generally refers to the body of commonly used actions and measures for climate change adaptation and differs from approaches (5.5.1) and options (5.5.2).

Much of the observed adaptation practice deals mainly with coastal hazards such as coastal erosion and coastal flooding, although imperfect at times (Hanak and Moreno 2012). In many parts of the world, small island indigenous communities address climate change consequences based on their own traditional knowledge (Percival, 2008; Langton *et al.*, 2012; Nakashima *et al.*, 2012).

Adaptation to sea level rise presents challenges on the ground as past adaptation to hazards may not be ecologically sustainable or economically affordable in light of some high-end sea level rise projections. Long-term adaptation to sea level rise has been confined to few major projects such as the Venice Lagoon project, the Thames Estuary 2100 project, London, and the Delta Works, Netherlands, (Norman, 2009) (Boxes 5-2 and 5-3). In addition, the complex nature of coasts as a socio-ecological system (5.2) makes adaptation practice challenging (Rosenzweig *et al.*, 2011).

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Box 5-2. London's Themes Estuary 2100 Plan: Adaptive Management for the Long Term

The Environment Agency in Britain, which has the main responsibility for flood risk management in England and Wales, has recently undertaken the project Themes Estuary 2100 (TE2100) to investigate the future flood threat to London (Environment Agency, 2012). The motivation was a fear that due to accelerated climate change-induced sea-level rise time could already be too short for replacing the Thames Barrier (build in 1982) and other measures that protect London, because such major engineering schemes take 25 to 30 years to plan and implement.

The US$20 million TE2100 project was designed to assess combinations of non-structural and structural engineering measures. Over a period of five years, many disciplines were involved, including engineers, economists, ecologists, geomorphologists and sociologists. The TE2100 Plan was developed in stages, with substantial involvement of the Estuary's stakeholders, using multi-criteria analysis to choose between the many competing options.

The main findings were:

- Anticipated sea-level rise is expected not to outstrip the existing defences in the short term: so there is time to plan future flood risk reduction measures.
- The Thames Barrier has a very high design standard (1 to 5,000 years), higher than had been originally anticipated: such key assets need to be made to last as long as possible.
- The Estuary is geomorphologically stable: a sudden change in its character and hence the risk of flooding is unlikely.
- The area affected contains as high density of with immensely valuable London properties, and developing substantially: risk is rising rapidly.

As a result an adaptive plan that manages risk in an iterative way was adopted, with numerous and diverse kinds of measures spread over the next 50 to 100 years, "pulling down" risk to acceptable levels (Figure 5-6). This plan includes an adaptive approach to managing the existing flood defence 'assets' (walls, barriers, gates) in a carefully planned way over the next 100 years (Penning-Rowsell *et al.*, 2012). During this time they will all need replacing, and could at the same time be enhanced. The plan also includes a strategy to restrict development in the flood risk areas, so that the time available for implementing major new works is not eroded by rapidly increasing risk. Finally, in the longer term (beyond c. 2070) there will be the need to plan for more substantial measures if sea-level rise accelerates. This might include a replacement of the Thames Barrier, with higher protection standards, probably nearer to the sea. In the meantime the adaptive approach requires careful monitoring of the drivers of risk in the Estuary to ensure that flood management authorities are not taken by surprise and forced into emergency measures.

[INSERT FIGURE 5-6 HERE
Figure 5-6: Adaptation measures and pathways considered in the TE2100 project. The boxed show the measures and extend over the range of sea level rise they are effective. The blue arrows link to alternative measures that may be applied once a measure is no longer effective. The red lines show the various sea-level rise scenarios used in the analysis. The fat green line shows a possible future adaptation pathway in the unlikely event of extreme change (>4 m rise).]

_____ END BOX 5-2 HERE _____

To date, certain principles and good practices (methods that have shown consistently better results and could be used as benchmark) can be derived from many observed examples of coastal adaptation. In a broad-scale assessment of climate change threats to Australia's coastal ecosystems, seven principles in adaptation were suggested: clearly defined goals for location, thorough understanding of connectivity within and between ecosystems, consideration of non-climatic drivers, involvement of all relevant stakeholders, easily available and shared data, re-thinking of existing policy and planning constraints and adaptation at local/regional scales (Hawden *et al.,* 2011). Based on Oxfam's adaptation programmes in South Asia that include coastal communities, additional principles include a focus on the poor, vulnerable and marginalized, community or local ownership, flexible and responsive implementation, preparation for future and capacity building at multiple levels (Sterrett, *et al.,* 2011). An assessment of worldwide case studies indicates the importance of knowledge transfer of good practice methods for scaling up adaptation strategies in and between regions and beyond the national scale (Martinez *et al.,* 2011).

For European coastlines facing coastal erosion, flooding and landslide events, more specific practices are given in a good practice guide (McInnes, 2006). In the California adaptation study that includes coasts, the lessons learnt include using best available science, decision on goals and early actions, locating relevant partners, identification and elimination of regulatory barriers and encouragement of introduction of new state mandates and guidelines (Bedsworth and Hanak, 2010). Boateng (2010) presented 15 case studies from 12 countries of best practice in coastal adaptation for surveyors. Bangladesh provides good examples in areas of raising awareness, disaster warning and control, and protective building measures (Martinez *et al.,* 2011)**.** In general, documentation on good adaptation practices for coasts is improving.

The issues for coastal adaptation are not radically different from issues encountered with integrated coastal zone management (ICZM) which offers an enabling environment for adaptation practice (Celliers *et al.,* 2013) (Box 5-4). A guidebook by USAID (2009) indicates the transfer of successful experience in ICZM to coastal adaptation. Detailed descriptions of adaptation measures are available in a number of guides or manuals (Linham and Nicholls, 2010; NOAA, 2010; Engineers Australia, 2012). Eleven types of structural projects have been identified for coastal protection and restoration for Louisiana (CPRA, 2012). The major difference of coastal adaptation from ICZM is coping with the dynamic nature of coastal areas, greater uncertainty, longer time frames in planning (beyond 30 years), and long-term commitments inherent in climate change.

Adaptation practice *is likely* to move forward as climate change adaptation (CCA) converges with disaster risk reduction (DRR) (ISDR, 2009; Setiadi *et al.,* 2010; Tran and Nitivattananon, 2011; Hay, 2012). Adaptation practice *is likely* to expand with two emerging approaches to adaptation in recent years – community-based adaptation (CBA) and ecosystem-based adaptation (EBA). CBA involves all relevant stakeholders especially local communities and is a bottom-up approach instead of the usual top-down (Ayers and Huq, 2009; UNDP, 2010; Riadh *et al.,* 2012) (Table 5-7). EBA includes innovative measures (Clark and Jupiter 2010; Crooks *et al.,* 2011; Girot *et al.,* 2012; Jones *et al.,* 2012; Mercer *et al.,* 2012) especially using mangroves for both CCA and DRR (Lacambra *et al.,* 2008; Spalding *et al.,* 2012).

In summary, adaptation practice in the coastal zone continues to meet challenges of climate change and sea-level rise (*very high confidence*). While more traditional adaptation practices may be revealed there is a myriad of adaptation practices depending on technology, policy, financial and institutional support, supported by documentation on good practices. ICZM with its emphasis on integration *is likely* to remain a major process for coastal adaptation. With a better understanding of coasts as a complex socio-ecological system, the future *is likely* to see a wider net and application of adaptation practices (*very high confidence*).

_____ START BOX 5-3 HERE _____

Box 5-3. Paradigm Shift in Adaptation to Rising Sea Levels in The Netherlands

Inhabitants in the low-lying coastal area of the Netherlands have been facing coastal and river flooding for centuries. Extreme sea levels together with long-term delta subsidence have been responsible for major catastrophic events causing thousands of fatalities over the last ten centuries. The expansion of habitable land and the increase in the population exposed to catastrophic events have co-existed with technological improvements for coastal protection and large investments resulting in a dramatic decrease in mortality rate (Van Baars and Van Kempen, 2009). Most of the coastal protection has been implemented during the second half of the twentieth century, resulting in the construction of large and numerous structures altering the appearance of an important part of the Dutch coastal area (Kabat *et al.*, 2009).

At present, nine million residents live in coastal areas at an elevation below sea level, where roughly 65% of gross national product is generated (Stive *et al.*, 2011). The anticipation of a changing climate, including sea-level rise, during the twenty-first century, together with an audit carried out in 2007 giving evidence of an aging flood protection system and an increasing vulnerability has renewed the demand for new plans for water and coastal management.

In this context the Dutch Government has set out far-reaching recommendations on how to keep the country flood-proof over the 21st century by considering a paradigm shift, namely addressing coastal protection 'working with nature' and providing 'room for river' instead of only 'fighting' the forces of nature with engineered structures (Figure 5-7). This takes into account a sea-level rise of as high as 0.65-1.3 by 2100. Some of the recommendations include soft and environmentally friendly solutions such as preserving land from development to accommodate increased river inundation; raising the level of lakes to ensure a continuous supply of fresh water; removing existing protection structures to restore natural estuary and tidal regimes; improving the standards of flood protection by a factor of 10 until 2050; maintaining coastal protection by beach nourishment, expanding the coast seaward in the next century and putting in place the necessary political-administrative, legal and financial resources. The estimated total cost of implementing this ambitious plan is €2.5-3.1 billion a year to 2050, representing a 0.5% of the current Dutch annual gross national product (Stive *et al.*, 2011).

[INSERT FIGURE 5-7 HERE
Figure 5-7: Overview of the Delta Committee National Recommendations. Source: Stive et al., 2011.]

Aerts *et al.* (2008) estimated today's economic damage from flooding based on differentiation according to water depth of all 53 dyke rings as approximately €190 billion covering both direct and indirect damage. The estimated future potential damage would be €400-€800 billion in 2040 and €3700 billion in 2100 in the absence of any measures, given a sea-level rise of 24-60 cm in 2040 and 150 cm in 2100. The factors that govern calculations of estimated future potential damage are economic growth combined with indirect damage. The Delta Committee suggested that, under the umbrella of this paradigm shift in the approach to water and coastal management, climate change offers key challenges that can result in societal and economic growth and evolution, moving the Netherlands into a sustainable country (Kabat *et al.*, 2009).

_____ END BOX 5-3 HERE _____

_____ START BOX 5-4 HERE _____

Box 5-4. Climate Change Adaptation and Integrated Coastal Zone Management in Developing Countries

Integrated Coastal Zone Management (ICZM) promotes sectoral and spatial integration of various activities in the coastal zone by establishing coordination across various sectors and government institutions with a view to sustainably developing coastal resources and protecting the environment. This makes it feasible for combining climate change adaptation with ICZM as a part of an integrative effort in coastal management.

ICZM in developing countries fostered by international organizations, in particular, struggle to meet the goals of ICZM (Isager, 2008). The drawbacks in the implementation of their ICZM act as constraints in climate change

adaptation within ICZM. For example, when initial funding by the external organizations disappears national governments have to step up to finance the cost of ICZM (Ibrahim and Shaw, 2012). Ineffective coastal governance is more visible in cases where the capacity of actors is low, the operation of single agency is dysfunctional, and subsequently, the integration of multiple coastal agencies is beyond the reach of many developing countries (Ibrahim and Shaw, 2012; Martinez *et al.*, 2011). Politics are also a strong force because of the involvement of various stakeholders, the hierarchy of government agencies and ministries, and the power of the majority political party or political leaders (Tabet and Fanning, 2012; Isager, 2008). Furthermore, the nature of public participation in developing countries differs from that in developed countries, and different norms and cultures need to be taken into account to assess public participation central to ICZM (Barale and Özhan, 2010). In some cases, there is lack of knowledge regarding the coastal systems (González-Riancho *et al.*, 2010).

As legal and institutional capabilities critical to the implementation of ICZM are often not available in developing countries, governments generate climate change adaptation strategies that are part of shoreline management plan, regional development, disaster management, and coastal resource management. Cases of adaptation strategies specific to climate change in practice are few as most are at the planning stage equipped with scenarios. Existing strategies derive from responses to coastal disasters and economic and social change affecting coastal livelihoods, for example, readily accessible and trained volunteers respond well by disseminating cyclone warnings and evacuating and rescuing people (WRI, 2007) and this could be translated into a strategy for climate change adaptation. Other strategies in progress or at the trial stage include forested buffer zones such as wetlands and mangroves (Mustelin *et al.*, 2011) and incremental migration. The long-term results and their replicability need to be further assessed.

To anticipate climate change and adapt, a variety of strategies could be used in the future. No or low-regret options provide co-benefits to the goals of sustainable development, livelihood improvement, and human well-being (IPCC, 2012). Combining different strategies are also increasingly under consideration (Cheong, 2011; Cheong *et al.*, 2013; Cartwright, 2009) including the blend of ecology and engineering such as mangrove planting, buffer zones and land use, and insurance and structural coastal defence (Yohe *et al.*, 2011). Adaptation planning on different geographic scales ranging from international, national, and regional in addition to local is at work. Regional adaptation strategies (Martinez *et al.*, 2011) and community-based adaptation (Cutter *et al.*, 2012) are both on the rise. Although ICZM can be a valuable policy framework to integrate climate change adaptation and coastal management, no studies of the effectiveness of ICZM combined with climate change adaptation in developing countries exist yet to assess its utility. Furthermore, there is a need for more detailed understanding of the science of coastal change at the local level that can be coupled with existing adaptation strategies of coastal communities.

_____ END BOX 5-4 HERE _____

5.5.5. Adaptation Opportunities, Constraints, and Limits

During the last years the attention on adaptation opportunities, constraints and limits has grown considerably aiming at a better assessment of our knowledge on adaptation strategies. In order to avoid the existing confusion on the contents of these terms, definitions provided in Chapter 16, Box 16-1 are used here.

There is a growing recognition of the potential co-benefits and new opportunities that can be achieved by mainstreaming adaptation with existing local to national goals and priorities (Chapter 14). Disaster Risk Reduction (DRR) and adaptation share the common goals of reducing vulnerability against impacts of extreme events while creating strategies that limit risk from hazards (IPCC, 2012). This is especially true in coastal areas where extreme flooding events due to severe storm surges are one of the main sources of hazard (Box 5-5). Besides, integrating adaptation with national and local planning can also contribute to build resilience in coastal areas. There is a *very high agreement high confidence* that Integrated Coastal Zone Management (IZCM) can make it possible for coastal regions to achieve their diverse goals in their adaptation to climate change (*limited evidence*) (5.5.1.4).

Ecosystems-Based Adaptation (EBA) is considered to be an emerging adaptation opportunity for adaptation (Munroe *et al.* 2011). In coastal area the conservation or restoration of habitats (e.g. mangroves, wetlands and

deltas) can provide effective measure against storm surge, saline intrusion and coastal erosion by using biodiversity and the ecosystem services they provide as a mean for adaptation (Jones *et al.,* 2012; Duarte *et al.* 2013, van Wesenbeeck, B.K., 2013, Borsje, *et al.*, 2011).

Since AR4 a variety of studies have been published producing a better understanding of the nature of the constraints and limits to adaptation, both generally (Chapter 16) and more specifically in the coastal sector (e.g., Lata and Nunn, 2011; Mozumber *et al.*, 2011; Storbjörk and Hedrén, 2011; Bedsworth and Hannak, 2010; Frazier *et al.*, 2010; Saroar *et al.*, 2010; Moser *et al.*, 2008; Tribbia and Moser, 2008; Ledoux *et al.*, 2005).

Researchers have categorized constraints in different ways (Chapter 16). The common link among all constraints is that they make adaptation less effective or they can lead to missed opportunities, difficult trade-offs, or higher costs. Several examples of constraints for specific for coastal adaptation can be found in the literature. Among others: polarized views in the community regarding the risk of sea level rise and concerns about fairness about retreat schemes in Australia (Ryan *et al.*, 2011); lack of awareness of sea level rise risks and spiritual beliefs in Fiji (Lata and Nunn 2011); insufficient budget for the development of adaptation policies and other currently pressing issues in the US (Mozumber *et al.*, 2011; Tribia and Moser, 2007 and 2008); distinct preferences for retreat options depending on several social and exposure conditions in Bangladesh (Saroar and Routray, 2010); need to provide compensatory habitats under the Habitats Regulations and lack of local public support in the UK (Ledoux *et al.* 2005).

The wide range of constraints identified in this assessment reflects different coastal management contexts, different foci on levels of governance and actors/decision-makers, as well as different methods used in identifying them. The commonly heard claim that lack of information is the main constraint to coastal adaptation is refuted by the wide range of constraints identified, and many of them are empirically shown to be more important than lack of locally relevant, credible information. (*high agreement, robust evidence*). Different constraints typically do not act in isolation, but come in interacting bundles (*high agreement, robust evidence*). Therefore it is difficult to predict which constraints matter most in any specific context but instead multiple constraints need to be addressed if adaptation is to move successfully through the different stages of the management process (*high agreement, moderate evidence*) (Moser and Ekstrom, 2010; Storbjörk, 2010; Londsdale *et al.*, 2010). Besides, some factors can act as enablers and add capacity to adapt, while acting as constraints at others (*high agreement, moderate evidence*) (Burch, 2010; Storbjörk, 2010).

Finally, a common concern emerging from the literature reviews (Biesbroek *et al.*, 2011; Ekstrom *et al.*, 2011) is that some critical constraints arise from the interactions across policy domains, existing laws and regulations, and long-term impacts of past decisions and policies (*high agreement, low evidence*). A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to existing objectives and values and prevent the loss of the key attributes, components or services of ecosystem (Chapter 16, Box 16-1; 16.2, 16.5) and may arise due to most of the constraints described above.

As with regards coastal areas, it is widely recognized that biophysical limitations arise, for example, in small developing island states where adaptation through retreat to increasing impact of sea level rise in conjunction with storm surges and flooding is not an option due to limited high land availability, creating a temporary and eventually permanent human displacement from low-lying areas (Green *et al.* 2009; Pelling and Uitto, 2001),(*high agreement, moderate evidence*). Nicholls *et al.* 2011, show that only a limited number of adaptation options are available for specific coastal areas if sea level exceeds a certain threshold (1 m) at the end of the century.

As with regards to natural (unassisted) adaptation, several researchers have examined particularly biophysical limits, e.g., of coastal marshes (Kirwan *et al.*, 2010a, b; Craft *et al.*, 2009; Langley *et al.*, 2009; Mudd *et al.*, 2009). Kirwan *et al.* (2010a) found that coastal marshes can adapt to conservative rates of sea-level rise (A1B), as long as there is sufficient sediment supply. By contrast, even coastal marshes with high sediment supplies, will *likely* submerge near the end of the 21st century under scenarios of more rapid sea-level rise (e.g., those that include ice sheet melting).

_____ START BOX 5-5 HERE _____

Box 5-5. Adaptation to Climate Change in the Framework of Coastal Disaster Management in Japan

Coastal disaster management in Japan is implemented through the Seacoast Law which was established in 1956 after the frequent severe natural disasters such as the Tonankai Earthquake Tsunami in 1944, Nankai Earthquake Tsunami in 1946 and Typhoon No. 13 in 1953. The aim of the law was to "protect the country's seacoast from damage due to sea or ground movement including, but not limited to, tsunami, storm surges and high waves". Later, in 1999, the law was amended to include "conservation of the coastal environment" and "promotion of proper use of the coast by public" in view of various functions of the coast. Under these laws the prefectural governors of each of 71 coastal zones covering the whole coastline in Japan shall established a master plan for coastal conservation. If deemed necessary to take management measures against damages the prefectural governor may designate seacoast conservation areas within the coastal zone. By 2010, about 14,200 km out of the total 35,300 km coastline have been designated and about 9,600 km was protected by coastal structures (River Bureau, 2011).

The crown height of coastal protection structures is determined from the height necessary of storm surges and tsunamis with an additional allowance. The sea-level rise at the time of design is taken into consideration by using the latest tide record. After the 2011 Tohoku Earthquake Tsunami, the Central Disaster Management Council (2011) decided to reconstruct protective coastal structures against the relatively frequent tsunamis (with a return period of several tens to one hundred and some years) and to save human lives by evacuation and all other means for the tsunami of the largest class based on scientific knowledge.

On this basis, the Committee on Adaptation Strategy for Global Warming in the Coastal Zone (2011) developed a manual for adaptation. According to the report, the land area below the mean sea level increases by about 50% in the three major bay areas (Tokyo, Nagoya and Osaka) if the sea level rises by 59 cm which is the highest projection in the IPCC (2007) Fourth Assessment Report. In the Tokyo Bay, the inundation area with a sea-level rise of 60 cm was predicted for Typhoon Muroto which landed on the western part of Japan in 1934 and is stronger than the present design typhoon by 40%. The results showed that 265 km^2 of the Tokyo metropolitan area would be inundated.

In order to develop an adaptation strategy, a case study on the criterion for priority was done. Two indicators were selected and calculated for each section of the land area. One indicator is evaluated from the age and earthquake resistance of the coastal structures in the section, reflecting the soundness of the structures and the urgency for improvement. The other reflects the effectiveness of the structural protection which is evaluated from the damage based on the assets in the predicted inundation area. Figure 5-8 shows the diagram for judging priority of adaptation to global warming. In Tokyo Bay, the allowance in the design crown height has absorbed the sea-level rise up to the present. However, adaptation to the future climate change needs to be implemented according to the diagram in parallel to improvement to aging coastal structures and earthquake resistance.

[INSERT FIGURE 5-8 HERE
Figure 5-8: Priority in investment for adaptation to global warming.]

_____ END BOX 5-5 HERE _____

5.5.6. Synergies and Tradeoffs between Mitigation and Adaptation

Klein *et al.* (2007, p. 749) defined trade-offs between mitigation and adaptation as the "balancing of adaptation and mitigation when it is not possible to carry out both activities fully at the same time (e.g., due to financial or other constraints)". Successful adaptive coastal management of climate risks will involve assessing and minimizing potential trade-offs with other non-climate policy goals (e.g., economic development, enhancement of coastal tourism) and interactions between adaptation and mitigation (e.g. Bunce *et al.*, 2010b; Barbier *et al.*, 2008; Tol 2007; Brown *et al.*, 2002).

A range of studies suggest that adaptation will be the predominant approach to reducing climate risks to coastal communities, populations, resources and activities over the 21st because large increases in sea-level rise cannot be

ruled out (WG1, Chapter 13, 13.5.2.) and because of the time lag between emission reductions, temperature changes and impacts on global sea levels (Nicholls *et al.*, 2011; Nicholls *et al.*, 2007). Systematic assessment of potential synergies and trade-offs between mitigation, adaptation, and other, non-climatic policy goals and efforts to maintain or increase flexibility to enable policy adjustments in the future have been proposed as strategies to recognize, avoid and minimize the risk of negative policy interactions (e.g., Vermaat *et al.* 2005; Nicholls *et al.*, 2011; Chapter 20, 20.3.3.).

Positive synergies and complementarities between mitigation and adaptation in the coastal sector exist. Marine vegetated habitats (seagrasses, saltmarshes, macroalgae or mangroves) contribute to 50% of the total carbon burial in ocean sediments and provide additional functions including the buffering of impacts against storm surges and waves, soil preservation, raising the seafloor and shelter for fish nursery or habitat protection (Duarte *et al.* 2013, Alongi, 2002, Kennedy and Björk, 2009). Consequently, restoration or ecosystem engineering of marine vegetated areas can be considered as a good example of positive synergies between adaptation and mitigation in coastal areas (Duarte *et al.* 2013, Jones, *et al.* 2012, Borsje *et al.* 2011).

Many coastal zone-based activities and various coastal management activities involve emissions of greenhouse gases, the reduction or cessation of some of the may have positive implications for both mitigation and adaptation. The reduction/cessation of offshore oil production will imply a reduction in liquid fuel-related GHG emissions but would also imply a reduced risk of oil spills, a reduction of stresses on the marine/coastal eco-systems and variable socio-economic impacts on human communities and public health (O'Rourke and Connolly, 2003). This may result in reduced vulnerability or increased resilience and consequently a positive for adaptation.

However, some of the coastal adaptation options may have potential negative implications on mitigation. Relocation of infrastructure and development out of the coastal floodplains (retreat) will imply increase in one-time GHG emissions due to rebuilding of structures and possible increase in sprawl and ongoing transportation-related emissions (Biesbroek *et al.* 2009). The building or upgrading of coastal protection structures or ports will also imply an increased energy use and GHG emissions related to construction (cement production) (Boden *et al.* 2011).

Similarly, actions beneficial for mitigation in coastal areas may result in potential negative impacts for adaptation. A more compact coastal urban design, increasing development in floodplains (Giridharan *et al.* 2007) or the development of offshore renewable energy introducing additional drivers on near- and offshore coastal and marine ecosystems and species, are some examples.

5.5.7. Commitment to Adaptation

Recent results (Meehl *et al.* 2012) from global coupled climate model simulations with the new RCPs scenarios to 2300 confirm AR4 (Meehl *et al.* 2007) and indicate that there is a commitment to further sea level rise even if temperatures stabilize due to different levels of mitigation measures. This is mostly due to thermal expansion of seawater and the melting of ice-sheets and glaciers (WG1, Chapter 13).

Table 5-2 summarizes projections from (WG1, Chapter 13) for different extended RCPs for time horizons ranging to 2500 and considering GHG concentrations > 700 ppm. Results show that with aggressive mitigation measures in RCP2.6 limiting global warming, sea level continues to rise after 2100. With more moderate (RCP4.5.) and little (RCP8.5) mitigation, larger ongoing increases in sea level are expected lasting for several centuries.

It can be concluded that since AR4, there is *high agreement* that benefits from mitigation are most immediate for ocean acidification and least immediate for impacts related to sea level rise. A detailed discussion on adaptation efforts mitigation efforts and residual impacts can be found in Chapter 19.

A limited number of studies have estimated impacts due to sea level rise under low or high emission scenarios. Pardaens et al (2011), using projections from two coupled climate models considered the effects on 21st century sea-level rise of mitigation policies, under which the global-mean air temperature stabilizes close to a 2^{o}C increase, relative to a scenario of business-as-usual (a variant of the A1B scenario). The model-averaged projected sea level

rise for 2090–2099 relative to 1980–1999 is 0.29 m–0.51 m and a reduced range under mitigation of 0.17 m–0.34 m, primarily due to reduced thermal expansion. To estimate impacts on coastal populations of the sea level rise projections, the Dynamic Interactive Vulnerability Assessment (DIVA) model was used. Results suggest that by the end of the 21st century and without adaptation around 55% of the 84 million additional people flooded from sea level rise per year globally, under the business-as-usual scenario, could be avoided under such mitigation.

On the other end Nicholls *et al.* (2011) considering an estimate of sea-level rise by 2100, between 0.5 m and 2 m, for a temperature rise of 4°C or more over the same time frame and no mitigation, showed that a real risk of the forced displacement of up to 187 million people over the century (up to 2.4% of global population) exists. By introducing upgrade of protection structures as an adaptation option, it is estimated that the likelihood of protection being successfully implemented varies between regions, and is lowest in small islands, Africa and parts of Asia.

In summary, mitigation plays a role in reducing climate change risk in coastal areas. The intensity and time scale varies depending on the impact considered. Even with aggressive mitigation options future sea-level rise will continue for centuries, but model results show that it can be slowed down, providing more time for long-term strategic adaptation measures to be adopted.

5.6. Information Gaps, Data Gaps, and Research Needs

This chapter has updated knowledge about the impacts of climate change on the coastal systems not in isolation but also from the perspective of overexploitation and degradation that have been responsible for most of the historical changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea-level rise on human systems.

That sea levels will rise is a confident projection of climate science but uncertainties around the magnitude of future sea lever rise remain large. It is very likely that GMSL rise during the 21sy century will exceed the observed rate for the period 1971-2100 (Chapter 13, WGI) and that sea level rise will continue to rise for several hundred years even if temperature is stabilized at 2-3^{o}C above pre-industrial values (Meehl *et al.*, 2012). However, many sea level rise assessments are not at spatial or temporal scales most relevant for decision makers who require information on baseline conditions and projections of change (Kettle, 2012) of relative sea level rise (i.e. including local subsidence) for vulnerability assessment and adaptation planning.

Quantitative predictions of future coastal change remain difficult despite the application of improvements in technology, e.g., aerial photographs, satellite imagery, LiDAR (Sesil *et al.*, 2009; Revell *et al.*, 2011; Pe'eri and Long, 2012) to investigate and characterize large-scale changes in shoreline. There is incomplete understanding of coastal changes over the decade and century timescales (Woodroffe and Murray-Wallace, 2012). Shoreline response is more complex than simple submergence because of factors such as sediment supply, offshore geology, engineering structures, and wave forcing (Ashton *et al.*, 2008).

The projection of the future impacts of climate change on natural systems is hampered by the lack of sufficiently detailed data at the required levels of space and time. Observed impacts on beaches, rocky coasts, wetlands, coastal aquifers or deltas area due to the joint effect of multi-drivers of climate and human-induced origin. There is still incomplete understanding of the relative role played by each of these drivers and, especially on their combined effect. Uncertainties are even higher when it comes to the evaluation of projected impacts. For coastal ecosystems virtually all data used to parametrize predictive models have been gathered during perturbation experiments involving only one driver, performed on isolated organisms in the laboratory, and on short periods of time (typically days to weeks). Reliable predictions require information on multifactorial experiments performed on communities (preferably in the field), and on time scale of months to years in order to take into consideration the processes of biological acclimation and adaptation.

Although sea level is projected to rise in future, there are significant gaps in vulnerability assessment of other specific coastal impacts. For example, climate modeling of diseases that could affect coastal areas is based mainly

on the mean values of climate. Also, despite tourism as one of most important industries in the coastal areas, not enough is known about tourists' behavioural reactions to projected climatic changes (Moreno and Amelung, 2009).

A wide range of coastal management framework and measures is available and used in coastal adaptation to climate change, and their scope for their integration has increased by combining scenarios of climate change and socio-economic conditions and risk assessment (Kirshen *et al.,* 2012). While various adaptation measures are available, at the local level, there remains insufficient information on assessment of adaptation options. Data and knowledge gaps exist or their reliability is insufficient. Despite the availability of potential useful climate information, a gap exists between what is useful information for scientists and for users in decision-making. The proposed actions to improve usability include varying levels of interaction, customization, value-adding, retailing and wholesaling (Lemos *et al.*, 2012) so that data and methods can be more openly-accessable to fellow scientists and public (Kleiner, 2011).

Coastal systems are affected by human and climate drivers and there are also complex interactions between the two. In general, where components of coastal systems are sensitive to temperature change, there is a greater degree of confidence that climate change has played a role. Data are available on the range shift in coastal plant and animal species and the role of higher temperatures on coral bleaching. However, in many cases in the human systems, the detected changes can be largely attributed to human drivers. Reducing our knowledge gaps on the understanding of the processes inducing changes would help to respond to them in an efficient way.

The economics of coastal adaptation is under researched. More comprehensive assessments of adaptation costs and benefits that simultaneously consider both the gradual impact of land loss due to sea level rise and the stochastic impacts of extreme water levels (storm surges, cyclones) are needed, as well as other impacts such as salt water intrusion, wetland loss and change and backwater effects. Assessments should also consider a more comprehensive range of adaptation options and strategies, including "soft" protection, accommodation and retreat options as well as the trade-offs between these.

Governance of coastal adaptation and the role of institutions in the transition towards sustainable coasts are under-researched. While institutional factors are recognized to be decisive in constraining and enabling coastal adaptation, there is little dedicated social science research aiming at understanding which institutional arrangement are effective in which socio-economic and biophysical contexts.

Developing a coastal adaptation knowledge network between scientists, policy makers, stakeholders and the general public could be considered as a priority area for coastal areas of large or regional areas affected by climate change and sea-level rise. This is well developed in the European Union, the Mediterranean and Australia but less so in the developing countries, except in certain regions, e.g. Caribbean islands, Pacific Islands.

Future research needs for coastal adaptation are identified by several developments in climate science. Based on Li *et al.* (2011) survey of the foci of climate research in the 21st century, the implications for coasts would be on biodiversity and flooding. Future technological advances may be significant, e.g., new forms of energy and food production, information and communication technology (ICT) for risk monitoring (Delta Commission, 2008) and these would be useful for flood risks and food production in deltas and coastal systems (aquaculture). With recent adverse climatic and environmental events on coasts, adaptation demands different decision regimes (Kiker *et al.*, 2010) but adaptation, mitigation and avoidance measures still require integrating research that includes natural and social sciences (CCSP, 2009). Although many gaps still remain, there is nevertheless a greater foundation of climate change research on coasts across a wide range of fields (Grieneisen and Zhang, 2011) upon which scientists, policymakers and public may find improved solutions for coastal adaptation.

Frequently Asked Questions

FAQ 5.1: How does climate change affect coastal ecosystems?

The major climate-related drivers affecting coastal ecosystems are sea-level rise, ocean warming and ocean acidification. The impact of sea level is mostly related to the capacity by animals (e.g. corals) and plants (e.g. mangroves) to keep up with the vertical rise of the sea. Ocean warming affects all organisms, increasing their

metabolism, causing mass mortality events of those living close their upper thermal limit, and/or affecting their geographical distribution. Ocean acidification negatively impacts many organisms that build shells and skeletons but its effects are poorly known at the ecosystem level.

FAQ 5.2: How is climate change influencing coastal erosion?

Coastal erosion can be caused by winds, waves and currents, especially during storms, as well as sea-level rise and for deltas, river sediment transport and deposition are important factors. Based on the simplest model, a rise in mean sea level usually results in a landward and upward displacement of the cross-shore seabed profile and a retreat of the shoreline. Increasing waves heights can cause the sand bars to move seawards and high storm surges (sea levels) also produce an offshore movement of sand due to non-equilibrium in the profile. Higher waves and surges may increase the probability of sand barrier and dune overwash or breaching. Changes in wave direction may result in increased sediment transport and subsequent erosion.

FAQ 5.3: How can coastal communities adapt to climate change impacts?

Various adaptation strategies are available which range from (managed) retreat, accommodation and protection. Adaptation through structural measures includes hard (e.g. sea walls) and soft (e.g. coastal revegetation) management options. Non-structural measures include land-use planning (e.g. rolling easements that require relocation of vulnerable infrastructure as critical risk thresholds are crossed) and climate-aware policies and plans, including EIA and building codes. Monitoring and compliance are required to ensure implementation of plans. Education is also important for building community resilience. Risk transfer mechanisms (e.g. insurance) address residual risk although where risks are too high, retreat from coastal areas may be the only viable response. A combination of strategies, tailored to suit the particular coastal community, may be required and will need to be reviewed and adjusted as circumstances change in the future.

FAQ 5.4: Does adequate planning for coastal uses contribute to a reduction in climate change risks?

Yes, adequate planning of coastal uses contributes to reduced climate change risks and lessens the chances of reactive responses to the impacts of extreme events. Such planning is normally supported by national legislation and considers both the problems of both climate change and coastal hazards, especially coastal flooding. Regional coastal strategies and plans are established with guidelines for local governments to implement. For measures to be taken, the focus is on precautionary measures irrespective of future climate change. An important paradigm change of planning land uses to reduce climate change is to use the buffer zone as a response to coastal inundation. The strategy is to work with nature rather than against nature, e.g. in the Netherlands. It should be noted that for many developing countries planning at the grass-root level either does not exist or is not yet workable requiring re-evaluation of how to make adaptation more sustainable..

FAQ 5.5: How does ocean acidification affect marine and coastal areas and islands?

PH, a measure of seawater acidity, has numerous implications on biological and geological systems. For example, in coastal systems, it plays a role in primary production which constitutes the base of the food chain, in the deposition of calcium carbonate in shells and skeletons, in the degradation of limestone, as well as in the abundance of certain forms of chemical elements and on their toxicity. Ocean acidification has therefore a lot of ramifications on the biology, ecology, biogeochemistry, and socio-economy of coastal systems. Some of these ramifications are well understood while others such as changes in coastal food-webs and fisheries are poorly known.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

[Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building (scleractinian) corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics. About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and are likely to derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including those from provisioning (food, construction material, medicine), regulating (shoreline protection, water quality),

supporting services (oxygen supply) and cultural (religion, tourism). This is especially true in small islands (29.3.3.1).

Most human-induced disturbances to coral reefs were local (e.g., coastal development, pollution, nutrient enrichment and overfishing) until the early 1980s when global and climate-related disturbances (ocean warming and acidification) began to occur. Temperature and seawater acidity are two of the most important environmental variables determining the distribution of coral reefs (Kleypas et al., 2001). As corals are centrally important as ecosystem engineers (Wild et al., 2011), the impacts on corals have led to widespread degradation of coral reefs.

A wide range of climatic and non-climatic stressors affect corals and coral reefs and negative impacts are already observed (5.4.2.4, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae (genus *Symbiodinium*), which live in the coral tissues and play a key role in supplying the coral host with energy and nutrients (Baker et al., 2008) (see 6.2.5 for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies, is the most widespread and conspicuous impact (Fig. 5X; see Sections, 5.4.2.4, 6.2.5, 25.6.2, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Elevated temperature along with ocean acidification reduces the calcification rate of corals (*high confidence*; 5.4.2.4), and may tip the calcium carbonate balance of reef frameworks towards dissolution (*medium evidence and agreement*; 5.4.2.4). These changes will erode fish habitats with cascading effects reaching fish community structure and associated fisheries (*robust evidence, high agreement*, 30.5).

Around 50% of all coral reefs have experienced medium-high to very high impact of human activities (30-50% to 50-70% degraded; Halpern et al., 2008), which has been a significant stressor for over 50 years in many cases. As a result, the abundance of reef building corals is in rapid decline (1 to 2% per year, 1997-2003) in many Pacific and SE Asian regions (Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and coral bleaching have led to a decline in coral cover on the Great Barrier Reef (about 51% between 1985 and 2012; De'ath et al., 2012).

One third of all coral species exhibit a high risk of extinction, based on recent patterns of decline and other factors such as reproductive strategy (Carpenter et al., 2008). Although less well documented, non-coral benthic invertebrates are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation coral reefs, including in a marine reserve (Jones et al., 2004). While many factors, such as overfishing and local pollution, are involved in the decline of coral reefs, climate change through its pervasive influence on sea temperature, ocean acidity, and storm strength plays a very significant role.

There is *robust evidence* and *high agreement* that coral reefs are one of the most vulnerable marine ecosystems (Chapters 5, 6, 25, and 30). Globally, more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011) even in the absence of climatic factors. Future impacts of climate stressors (ocean warming, acidification and sea level rise) will exacerbate the impacts of non-climatic stressors (*high agreement, robust evidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9–60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation under the RCP3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30–88%, 68% uncertainty range). If present day corals have residual capacity to acclimatize and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan et al., sbm). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia & Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton et al. (2012) are already exploiting their coral reef fisheries in an unsustainable way (13.X.X).

- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4, 30.5).

Coral reefs make a modest contribution to the global domestic product but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent on average 5% of the GDP of South Pacific islands (Laurans et al., 2013). At the local scale, these two services provide at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are less effective in reducing coral loss from thermal stress (Selig et al., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012). Controlling the input of nutrients and sediment from land is an important complementary management strategy because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2012). There is also high confidence that, in the long term, limiting the amount of warming and acidity is central to ensuring the viability of coral reef systems and dependent communities (5.X.X and 30.5).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction

Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult;

observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other

potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

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Box CC-TC. Case Study Building Long Term Resilience from Tropical Cyclone Disasters

[Yoshiki Saito (Japan), Kathleen McInnes (Australia)]

Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves and storm surge, all of which can have major impacts on society and ecosystems. For example, Bangladesh and India account for 86% of mortality from tropical cyclones (Murray *et al.*, 2012), which is mainly due to the rarest and most severe storm categories (i.e. Categories 3, 4, and 5).

About 90 tropical cyclones occur globally each year (Seneviratne et al, 2012) although interannual variability is large. Changes in observing techniques particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities. Therefore, SREX concluded that there is *low confidence* that any observed long-term (i.e. 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne, *et al.*, 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is *likely* to increase. Regionally specific projections have *lower confidencelower confidence* (see WG1 Box 14.2).

Longer term impacts from tropical cyclones includes salinisation of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer term changes associated with climate change.

Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density in expanding urban areas (Nicholls *et al.*, 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray *et al.*, 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga *et al.*, 2003; Brakenridge *et al.*, 2012). The flooded areas were captured by a NASA MODIS image on 5 May 2008 (Figure TC-1).

[INSERT FIGURE TC-1 HERE
Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al.*, 2012).]

Murray *et al.* (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargs in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation (Murray et al, 2012). Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3,400 compared to over 138000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multi-storied cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. Birkmann and Teichman, (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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Table 5-1: Projections of global mean sea level rise in metres relative to 1986–2005 based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5-95% range is given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available (source: WG1, Chapter 13).

	RCP	2080-2100	2100	2200	2300	2400	2500
Low	2.6	0.42 [0.29 to 0.55]	0.46 [0.32 to .61]	0.47–0.60	0.59–0.67	0.67–0.79	0.77–0.91
Medium	4.5	0.49 [0.36 to 0.63]	0.56 [0.41 to .71]	0.25–0.90	0.31–1.12	0.30–1.38	0.27–1.67
High	6.0	0.50 [0.37 to 0.64]	0.58 [0.42 to .74]	0.67–1.92	1.10–3.21	1.44–4.55	1.80–5.76
	8.5	0.64 [0.48 to 0.82]	0.76 [0.56 to .96]				

Table 5-2: Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects (↑ increase; ↓ decrease; ⊄ no change; ? uncertain; ↔ regional variability).

Climate Driver	Physical effects	Trends	Projections	Progress since AR4
Sea Level	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change).	GMSL *very likely* (5.3.2.2, WG1 Ch. 13)	GMSL *very likely* (see Table 5.1, WG1 Ch. 13) « (5.3.2.2, WG1 Ch. 13)	Improved confidence in contributions to observed sea level. More information on regional and local SLR.
Storms (Tropical cyclones (TC's), extratropical cyclones (ETC's)	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change). Coastal infrastructure damage and flood defence failure.	TC's (Box 5.1, WG1 2.6.3) *Low confidence* in trends in frequency and intensity due to limitations in observations « ETC's (5.3.3.1 WG1 2.6.4) *Likely* poleward movement of circulation features but *low confidence* in intensity changes.	TC's (Box 5.1) *Likely* ¯ - Ë in frequency; *Likely* ↑ in the most intense TC's ETC's (5.3.3.1) *High confidence* that reduction of ETC's will be small globally. *Low confidence* in changes in intensity.	Lowering of confidence of observed trends in TC's and ETC's since AR4. More basin-specific information on storm track changes.
Winds	Wind waves, storm surges, coastal currents, coastal infrastructure damage.	*Low confidence* in trends in mean and extreme wind speeds (5.3.3.2, SREX, WG1 Ch 2).	*Low confidence* in projected mean wind speeds. *Likely* increase in TC extreme wind speeds (5.3.3.2, SREX).	Winds not specifically addressed in AR4.

Waves	Coastal erosion, overtopping and coastal flooding.	*Likely* positive trends in high latitudes (5.3.3.2, WG1, Ch 3).	*Low confidence* for projections overall but *medium confidence* for southern ocean increases (5.3.3.2).	Large increase in number of wave projection studies since AR4.
Extreme Sea Levels	Coastal flooding erosion, saltwater intrusion	*High confidence* of increase due to GSLR (5.3.3.3, WG1 Chapter 13).	*High confidence* of increase due to GSLR, *low confidence* of changes due to storm changes (5.3.3.3, WG1 Chapter 13) «	Local subsidence is an important contribution to RSLR in many locations.
Sea Surface Temperature	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms.	*High confidence* that coastal SST increase is higher than global SST increase « (5.3.3.4, WG1 Ch. 3).	*High confidence* that coastal SSTs will increase with projected temperature increase (5.3.3.4).	Emerging information on coastal changes in SSTs.
Freshwater Input	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply.	*Mmedium confidence (limited evidence)* in a net declining trend in freshwater input.	*Medium confidence* for general increase in high latitudes and wet tropics and decrease in other tropical regions «.	Emerging information on freshwater input.
Ocean Acidity	Increased CO2 fertilisation; decreased seawater pH and carbonate ion concentration (or 'ocean acidification') [this is not a "Physical effect"]	*High confidence* of overall increase, with high local and regional variability (5.3.3.5).	*High confidence* of increase at unprecedented rates but with local and regional variability (Box CC-OA).	OA not specifically addressed in AR4. Considerable progress made in chemical projections and biological impacts.

Table 5-3: Top ten nations with the largest populations and the highest proportions of population in low-lying coastal areas (Countries with fewer than 100,000 inhabitants are not included; 15 SIDs (Small Island Developing States) with total of 423,000 inhabitants are also excluded). Source: Bollman *et al.*, 2010.

Top ten nations classified by population in low-lying coastal regions			Top ten nations classified by proportion of population in low-lying coastal regions		
Nation	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions	Nations	Population in low-lying coastal regions (10^3)	% of population in low-lying coastal regions
1. China	127,038	10 %	1. Maldives	291	100 %
2. India	63,341	6 %	2. Bahamas	267	88 %
3. Bangladesh	53,111	39 %	3. Bahrain	501	78 %
4. Indonesia	41,807	20 %	4. Suriname	325	78 %
5. Vietnam	41,439	53 %	5. Netherlands	9590	60 %
6. Japan	30,827	24 %	6. Macao	264	59 %
7. Egypt	24,411	36 %	7. Guyana	419	55 %
8. USA	23,279	8 %	8. Vietnam	41,439	53 %
9. Thailand	15,689	25 %	9. Djibouti	250	40 %
10. Philippines	15,122	20 %	10. Bangladesh	53,111	39 %

Table 5-4: Main impacts of relative sea-level rise. Adapted from Nicholls 2002 and Nicholls *et al.* 2010.

Biophysical impacts of relative sea-level rise	**Other climate drivers**	**Other human drivers**
Dryland loss due to submergence	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Flood damage (due to surges, tropical cyclones)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Backwater effect (river)	Runoff	Catchment management and land use
Wetland loss (and change)	Sediment supply, CO_2 fertilization,	Sediment supply, migration space, direct destruction
Dryland loss due to erosion	Sediment supply, wave and storm climate	Sediment supply
Saltwater intrusion into surface waters	Runoff	Catchment management and land use
Saltwater intrusion into ground waters	Precipitation	Land use, aquifer use
Rising water tables/ impeded drainage	Precipitation	Land use, aquifer use

Table 5-5: Summary of Coastal Vulnerability Assessments conducted at national or regional scale. Studies that either costed (Adapt$) or considered adaptation options (Adapt) are indicated. In studies that have considered adaptation: WOA=without adaptation; WA=with adaptation. CVI=Coastal Vulnerability Index; GIS=Geographic Information System, DIVA=Dynamic Interactive Vulnerability Assessment model. RSLR=relative sea level rise.

Location	Physical impacts considered	SLR scenario	Socio-economic scenario	Physical and ecosystem vulnerability	Human system vulnerability	Method and tools	Reference
Africa							
Africa	Erosion, flooding	0.64-1.26 m SLR by 2100, plus local subsidence/ uplift	IMAGE model scenario		WOA: 16–27 million people flooded and US$5-9 billion annual damage costs WA: Adaptation cuts people flooded by two orders of magnitude and damage costs by half, adaptation deficit US$300 billion and annual costs US$2-6 billion	DIVA (Adapt$)	Hinkel *et al.*, 2011
Ghana (east coast)	Erosion, submergence	1-5m SLR		Possible erosion of existing coastal buffer zones that separate open coast from coastal lagoons and inundation of coastal plains		GIS	Boateng, 2012b
Tanzania (Dar-es-Salaam)	Flood exposure	0.13-0.66 m by 2070, plus local subsidence/ uplift, plus to 1-in-100 event	A1 with rapid urbanization		210,000 people and US$10 billion exposed to 100-year coastal flood by 2070	GIS	Kebede and Nicholls, 2012
Asia							
China				Sediment supply to major delta regions has reduced by 50% since early 1980's and is driving coastal erosion			Cai *et al.*, 2009
China	Flooding, erosion	Current rate of RSLR (average 6mm/yr)		Vulnerability to flooding and erosion of the 18,000 km coastline, is ranked very high-3%; high-29%; moderate- 58% and low-10%.		CVI	Yin *et al.*, 2012
East Timor	Flooding, erosion wetland loss, salt water intrusion	0.31-0.54 m by 2100, plus local subsidence / uplift	A2 and B1	Wetland area reduction under 0.54m SLR is greatest for the Solomon Islands (68%), the Philippines (51%) and East Timor (50%). Composition of wetland areas in 2100 change to include more mangroves and less unvegetated wetland areas in 2100 compared to 2010. Increased salinity intrusion up major rivers 14-27% under A2	Expected number of people flooded annually relative national population (pop): WOA 0.54% pop A2; WA 0.01% pop A2	DIVA (Adapt$)	McLeod *et al.*, 2010
Indonesia					WOA 1.19% pop A2; WA 0.00% pop A2		
Malaysia					WOA 0.46% pop A2; WA 0.00% pop A2		
Papua New Guinea					WOA 0.07% pop A2; WA 0.01% pop A2		
Philippines					WOA 0.80% pop A2; WA 0.00% pop A2		
Solomon Islands					WOA 0.27% pop A2; WA 0.00% pop A2		

				Increased salinity intrusion into land areas 7-12% under A2			
India (Udupi coast)	Erosion, submergence	1-10m SLR		Erosion risk: of the 95 km of coastline, 59% assessed as very high; 7%high, 4% moderate, 30% low erosion risk. 372-42 km^2 exposed to submergence from 1m SLR	Qualitative assessment of affected areas include residential and recreational areas, agricultural land and the natural ecosystem	CVI	Dwarakish *et al.*, 2009
Vietnam	Submergence exposure	1-5m			Exposure is largest in Red River and Mekong deltas. Options identified to prolong the use of these areas into the future	GIS	Boateng, 2012a
Australasia							
Australia	Flood exposure, Erosion	1.1 m, combined with either 1-in-100 year flood event or mean high tide level		Exposure to tropical cyclone related hazards across northern half of continent, health of Great Barrier Reef will affect coastal resilience in NE. Southern coastline with extensive cliffs, large bays, estuaries, gulfs and flats vulnerable to SLR inundation and cliff instability if wave climate changes. Greater erosion along populous eastern coast due to SLR and storm changes.	Potential inundation of, 157,000–247,600 of the 711,000 existing residential buildings close to water. Nearly 39,000 buildings at risk from erosion due to SLR. Indigenous communities, including island based deemed particularly vulnerable due to their remoteness and location on low elevation land.	GIS coastal geomorphology model and Bruun Rule GIS DEM infrastructure database	Department of Climate Change, 2009
Australia (Victoria)	Flood exposure	0.8-1.4 m SLR by 2100, plus 1-in-100 year flood event		Across 9 coastal settlements considered, area exposed to 1-in-100 flood ranges from 153 to 408 km^2 for 0-1.4 m SLR	Across 9 coastal settlements considered, land parcels exposed to 1-in-100 flood ranges from 2,362 to 47,102 for 0 to1.4 m SLR	Hydrodynamic modelling, GIS	McInnes *et al.*, 2011
Europe							
Croatia	Submergence exposure	0.2-0.86 m SLR		A long narrow steep coastline with one major reclaimed alluvial plain will become increasingly vulnerable to inundation particularly for larger SLR projections. Erosion of pocket beaches will increase.	Sewage systems, agriculture and maritime transport and tourism affected by greater flood frequency of low-lying land and berths and piers.	Qualitative assessment	Baric *et al.*, 2008
Denmark-Copenhagen	Flood exposure	0.0-1.25 m SLR			Copenhagen not highly vulnerable to coastal flooding due to existing flood protection. WOA: direct costs of 1-in-100 year event increase from €3-4.8 billion with 0.5m SLR	GIS (Adapt)	Hallegatte *et al.*, 2011
Estonia	Submergence exposure	1 m SLR adjusted for regional uplift (i.e.		Observed beach erosion has resulted from increased storminess in the eastern Baltic Sea, combined with decline in winter sea-ice cover. Future	Possible productivity benefit from longer growing season. Major towns are not threatened due to location inland and mitigating effects of uplift. Sandy beaches and emerging coastal	Qualitative assessmen	Kont *et al.*, 2008

		69–73 cm RSLR)		land loss will impact major bird breeding grounds	tourism at risk.	t	
France	Flood exposure, erosion	0.88 m SLR + 5.8m surge (Atlantic) and 2.7 m surge (Mediterranean)		Atlantic coast with extensive dune systems is assessed as more resilient to rising sea levels over the coming century compared with Mediterranean coast where narrow dune systems are highly urbanized		GIS	Vinchon *et al.*, 2009
Germany	Submergence exposure	1 m SLR		There is a high level of reliance on hard coastal protection against extreme sea level hazards which will increase ecological vulnerability over time	300,000 people exposed in the coastal cities and communities. Erosion and flooding risks US$300 billion (based on 1995 values) of assets	GIS DEM, land-use, socio economic data	Sterr, 2008
Great Britain	Erosion, submergence	0.8 – 1m SLR		Large parts of the coasts are presently sediment starved and eroding and this will continue	At the national scale, economic losses due to erosion are expected to remain considerably smaller than flood losses	Qualitative assessment	de la Vega-Leinert and Nicholls, 2008
Norway	Submergence	0.5 - 1m SLR		Nationally, low susceptibility to accelerated sea-level rise due to mainly steep and resistant coastlines	Extensive infrastructure on northern and western coastlines likely to be negatively affected by sea-level rise, and adaptation costs could be significant	Qualitative assessment	Aunan and Romstad, 2008
Poland	Submergence	0.3 – 1m SLR		Lagoons, river deltas and estuaries in the far east and west were considered most vulnerable		Qualitative assessment	Pruszak and Zawadzka, 2008
Portugal	Submergence	0.14-0.57 m by 2100 SLR		Estuaries and coastal lagoons are assessed as most vulnerable and already sediment starved coastal beaches will continue to erode		Qualitative assessment	Ferreira *et al.*, 2008
Turkey	Submergence	1 m SLR			Without adaptation, impacts could cost 6% of current GNP. Adaptation/protection could cost 10% of current GNP.	Qualitative (Adapt)	Karaca and Nicholls, 2008
European Union	Erosion, flooding, salinity intrusion	0.35-0.45 m by 2100 SLR	A2 and B1		WOA: 0.2-0.8 million people flooded and US$17 billion annual damage costs WA: adaptation cuts exposure by a factor of 100 and annual damage costs by a factor of 10.	DIVA (Adapt$)	Hinkel *et al.*, 2010
N. America							
US	Submergence exposure	Land below 6 m above			20 municipalities with populations greater than 300,000 and 160 municipalities	GIS	Weiss *et al.*, 2011

		MHHW			with populations between 50,000 and 300,000 have land area with elevations at or below 6 m and connectivity to the sea,		
US	Land loss due to submergence	0.19-1.26 m SLR by 2100	2% annual GDP growth		WA: Total cost (adaptation plus residual damage) of US$ 50-75 billion (discounted at 3%)	GIS, CBA of protection vs. retreat (Adapt$)	Neumann *et al.*, 2010
US South Florida	Land loss due to submergence	0.5, 1.0, 1.5 m SLR by 2100 combined with MHHW		Submergence affects areas of ~1300 km^2, ~1700km^2, ~ 3000 km^2 respectively for SLR scenarios considered	~68000, ~210000, ~750000 population exposed population to SLR scenarios respectively $8 billion, $47 billion, $144 billion exposed to SLR scenarios respectively	GIS	Zhang, 2011
US Florida Keys	Land loss due to submergence	0.3, 0.6, 0.9, 1.2, 1.5, 1.8m SLR by 2100 combined with MHHW		Submergence affects areas of ~82 km^2, ~95km^2, ~ 107 km^2, ~119 km^2, ~127km^2, ~ 133 km^2 respectively for SLR scenarios	2663, 6403, 11,026, 15933, 19802, 21768 population exposed population to SLR scenarios respectively ~$56 million, ~$367 million, ~$2 billion, ~$6 billion, ~$9 billion, ~$12 billion exposed to SLR scenarios respectively	GIS	Zhang et al, 2011
US	Land loss due to submergence	0.67 m by 2100			Under the mid-SLR scenario (), approximately 1,630,000 people are potentially affected by SLR. Of these, 332,000 (~20%) are among the most socially vulnerable.	GIS & Social Vulnerability Index (SoVI)	Martinich et al, 2012
NW territories (Canada)	Shoreline stability and population exposure	Temperature, wind patterns		Loss of sea ice and shorter winter season and more variable weather patterns lead to changes in coastal sea ice coverage. Effects on species health and numbers.	More hazardous travel conditions for traditional hunting practices. Loss of traditional knowledge, skills and values.	Qualitative (Adapt)	Pearce *et al.*, 2010

Table 5-6: Impacts of sea level rise, coastal floods, and storms on critical coastal infrastructure by sector. Sources: Horton and Rosenzweig (2010), Zimmerman and Faris (2010).

Communications	Energy	Transportation	Water and waste
Higher average sea level			
• Increased salt water encroachment and damage to low-lying communications infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, causing increased maintenance cost and shortened replacement cycles • Tower destruction or loss of function	• Increased rates of coastal erosion and/or permanent inundation of low-lying areas, threatening coastal power plants and refineries • Increased equipment damage from corrosive effects of salt water encroachment resulting in higher maintenance costs and shorter replacement cycles	• Increased salt water encroachment and damage to infrastructure not built to withstand saltwater exposure • Increased rates of coastal erosion and/or permanent inundation of low-lying areas, resulting in increased maintenance cost and shorter replacement cycles • Decreased clearance levels under bridges	• Increased salt water encroachment and damage to water and waste infrastructure not built to withstand saltwater exposure • Increased release of pollution and contaminant runoff from sewer systems, treatment plants, brownfields and waste-storage facilities • Permanent inundation of low-lying areas, wetlands, piers, and marine transfer stations • Increased salt water infriltration into distribution systems transfer stations
More frequent and intense coastal flooding			
• Increased need for emergency management actions with high demand on communications infrastructure • Increase damage to communications equipment and infrastructure in low-lying areas	• Increased need for emergency management actions • Exacerbated flooding of low-lying power plants and equipment, as well as structural damage to infrastructure due to wave action • Increased use of energy to control floodwaters • Increased number and duration of local outages due to flooded and corroded equipment	• Increased need for emergency management actions • Exacerbated flooding of streets, subways, tunnel and bridge entrances, as well as structural damage to • Decreased levels of service from infrastructure due to wave action flooded roadways; increased hours of delay from congestion during street-flooding episodes • Increased energy use for pumping	• Increased need for emergency management actions • Exacerbated street, basemend and sewer flooding, leading to structural damage to infraesctructure • Episodic inundation of low-lying areas, wetlands, piers, and marine transfer stations

Table 5-7: Community-based adaptation options.

Impact	Type of option	Option	Brief description	References
Salinity	New and diversified livelihoods	Saline-tolerant crop cultivation	Farmer production of saline-tolerant multi-vegetable varieties and non-rice crops.	Rabbani *et al.* 2013; Ahmed 2010
	New and diversified livelihoods	Keora nursery	Mangrove fruit production to develop local female entrepreneurship.	Ahmed 2010
	New and diversified livelihoods	Crab fattening	Collection, rearing and feeding of crabs for 15 days to increase local market value.	Pouliotte *et al.* 2009
	Structural	Homestead protection	Houses constructed on raised foundations to mitigate salinity ingress.	Ayers and Forsyth 2009
Flooding /Waterlogging	Socio-technical	Disaster management committees	Multi-community stakeholder committees established to discuss disaster preparedness and response on a monthly basis.	Ahammad 2011
	Socio-technical	Early flood warning systems	Established systems converted into a language and format understood by local communities; warning dissemination through community radio services.	Ahmed 2005; Saroar and Routray 2010
	New and diversified livelihoods	Aquaculture: cage and integrated approaches	Small-scale fish culture in cages on submerged agriculture land; aquaculture integrated with other livelihood practices.	Pouliotte *et al.* 2009; Khan *et al.* 2012; Pomeroy *et al.* 2006
	New and diversified livelihoods	Embankment cropping	Growing different vegetable varieties around heightened shrimp enclosures/coastal polders for productive use of fallow land.	Ahmed 2010
	New and diversified livelihoods	Hydroponics	Cultivating vegetables and other crops on floating gardens.	Dev 2013; Ahmed 2010; Ayers and Forsyth 2009
Cyclones / storm surges	Structural/hard	Homestead reinforcement	Low-cost retrofitting to strengthen existing household structures especially roofs; strict implementation of building codes.	Ahmed 2010; Sales 2009
	Structural/soft	Homestead ecosystem protection	Plantation of specific fruit trees around homestead area.	Haq *et al.* 2012
	Structural/hard	Underground bunker construction	Underground bunker established providing protected storage space for valuable community assets.	Raihan *et al.* 2010
Sea-level rise (SLR)	Institutional	Risk insurance mechanisms	Farmers educated on comprehensive risk insurance focusing on sea-level rise and coastal agriculture.	Khan *et al.* 2012
Multi-coastal impacts	Institutional	Integrating climate change into education	Formal and informal teacher training and curriculum development on climate change, vulnerability and risk management.	Ahmed 2010
	Institutional	Integrated coastal zone management plan (ICZM)	ICZM plan development at local institutional level including land and sea use zoning for ecosystem conservation.	Sales 2009
	Structural / soft	Restoration, regeneration and management of coastal habitats	Community-led reforestation and afforestation of mangrove plantations including integration of aquaculture and farming to increase household income levels.	Sovacool *et al.* 2012; Rawlani *et al.* 2011

	Institutional	Community participation in local government decision-making	Active female participation in local government planning and budgeting processes to facilitate delivery of priority coastal adaptation needs.	Faulkner and Ali 2012
	Institutional /socio-technical	Improved research and knowledge management	Establishment of research centres; community-based monitoring of changes in coastal areas.	Rawlani *et al.* 2011; Sales 2009

Table 5-8: Global assessments of costs of sea-level rise.

Reference	**Physical impacts**	**SLR scenario**	**Socio-economic scenario**	**Impact indicators**	**Without adaptation**	**With adaptation**
Anthoff *et al.*, 2010	Submergence, wetland loss	0.5-2.0m SLR by 2100	A1, A2, B1, B2	Net present value of total cost for 2005-2100 (pure rate of time preference 1%)	US$ 800-3300 billion in 2100	US$200-2200 billion in 2100
Nicholls *et al.*, 2011	Submergence, erosion	0.5-2.0 m SLR by 2100	A1FI	Cumulative number of people displaced due to land loss to submergence and erosion	72-187 million people during 21st century	0.04-0.3 million people during 21st century
				Annual adaptation cost	N/a	US$ 25-270 billion/yr
Hinkel *et al.*, 2012	Flooding	0.6-1.3m by 2100	UN medium fertility	Annual expected number of people flooded	170-260 million people/yr in 2100	Two orders of magnitude smaller than w/o adaptation
				Annual total cost (including dike upgrade, dike maintenance and residual damage cost)	US$ 160-300 billion/yr in 2100	US$ 30-90 billion/yr in 2100
				Annual total cost relative to GDP	0.05% -0.09% of global GDP in 2100	0.01%-0.03% of global GDP in 2100

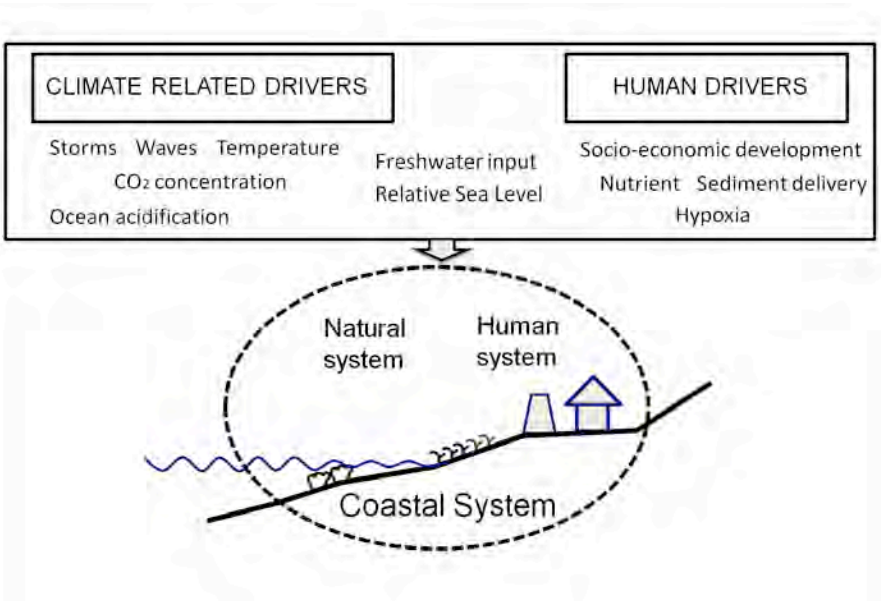

Figure 5-1: Schematic diagram indicating the elements of the coastal zone that are considered in this chapter.

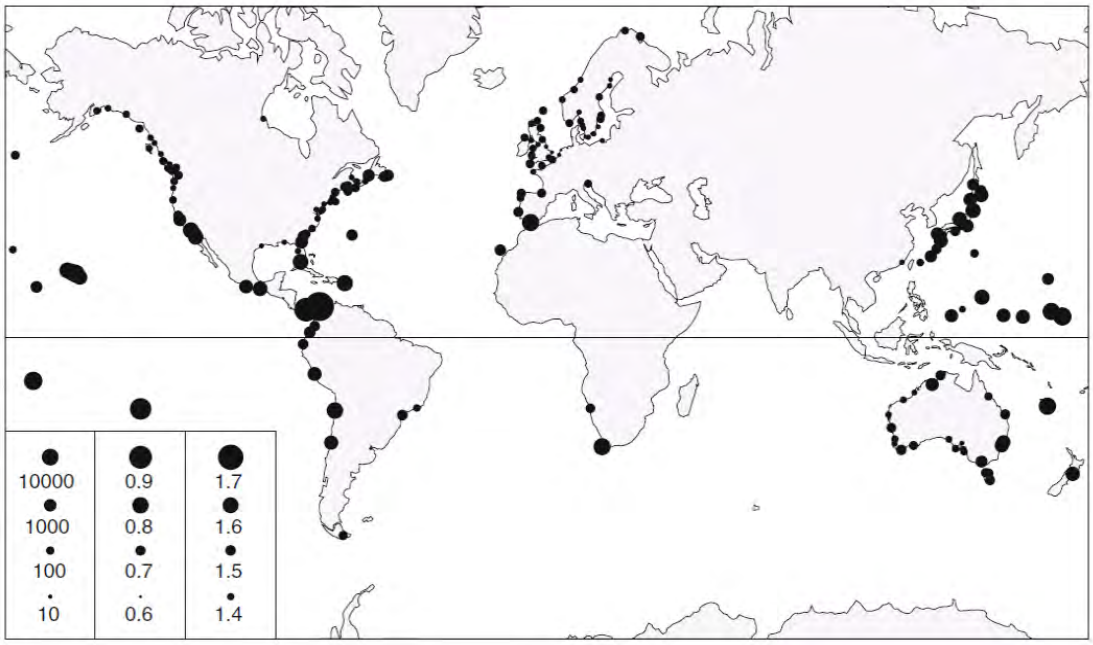

Figure 5-2: Results of global analysis, indicated by dot diameter. a Factor by which frequency of flooding events will increase with a rise in sea level of 0.5 metres (key is left-hand column of dots in the bottom left-hand corner). b Sea-level rise allowance (metres) for 1990–2100 which conserves frequency of flooding events for the IPCC A1FI Projection based on A1FI emission scenario and AR4-adjusted TAR projections (normal distribution with Δz=0.542 m and σ=0.168 m); key is central column of dots in the bottom left-hand corner. c Sea-level rise allowance (metres) for 21st century which conserves frequency of flooding events for the 1.0/1.0 m Projection, based on post-AR4 results (raised cosine distribution with Δz=1.0 m and W/2=1.0 m); key is right-hand column of dots in the bottom left-hand corner.

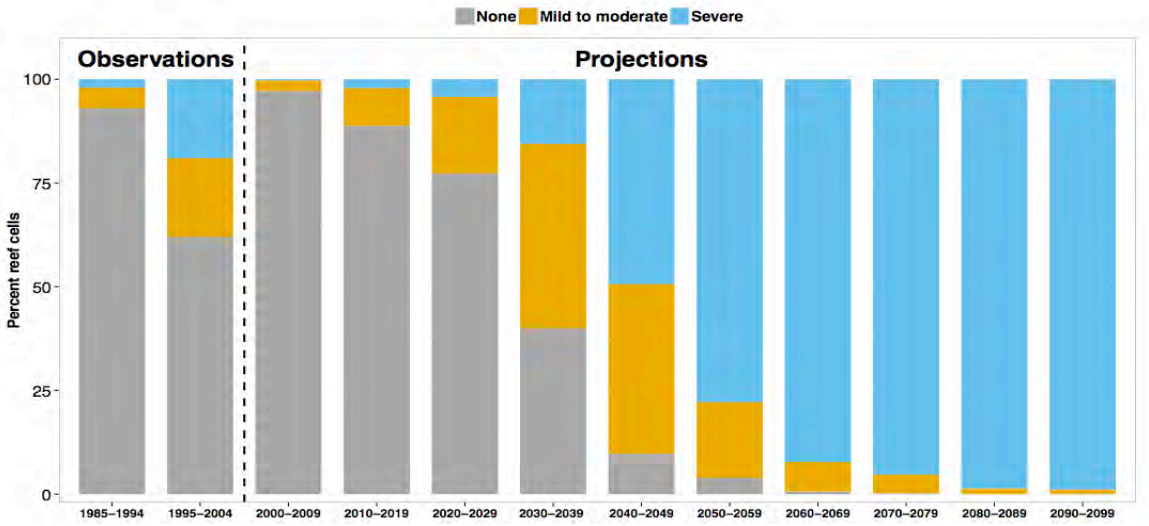

Figure 5-3: Percent of reef locations (1°x1° grid cells which have coral reefs) that experience no bleaching (green), at least one mild bleaching event (reddish-brown), or at least one severe bleaching event (purple) for each decade. Observed bleaching events are summarized from the ReefBase dataset (Kleypas *et al.* 2008). In the observations, some of the "no bleaching" cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the SRES A1B CO_2 scenario and the standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are not shown.]

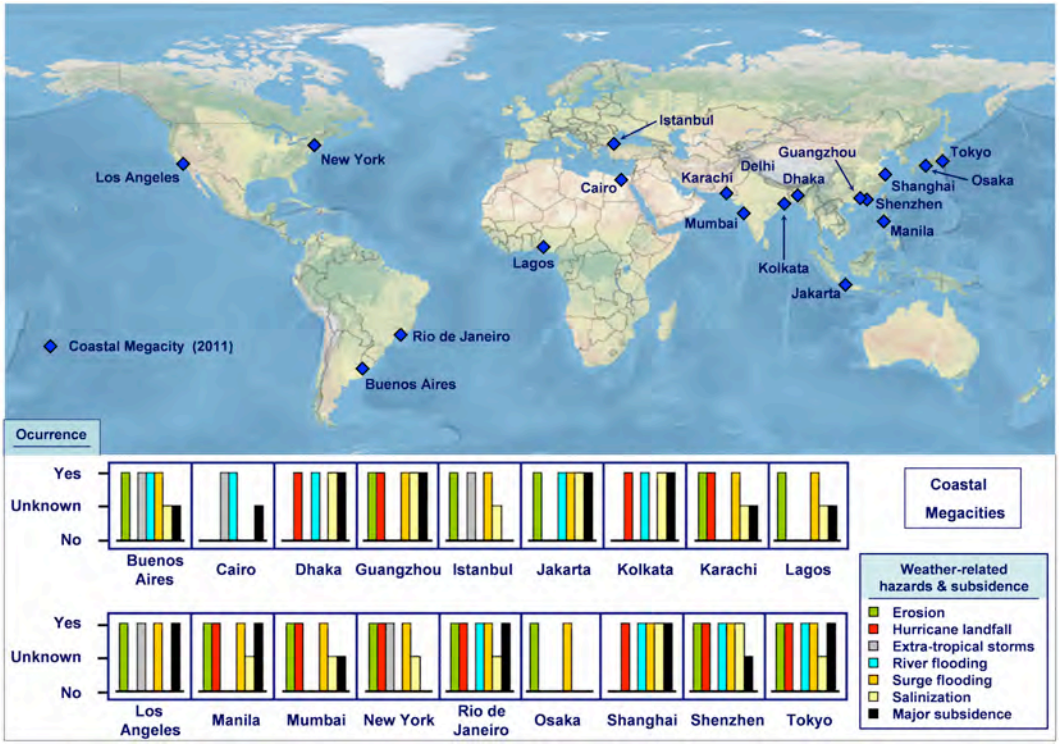

Figure 5-4: Mega-urbanisation on the coast. Source:Blackburn S and Marques da Silva C (2013) Mega-urbanisation on the coast: Global context and key trends in the twenty-first century, in Pelling M and Blackburn S (eds) Megacities and the Coast: Risk, Resilience and Transformation, Earthscan: London.

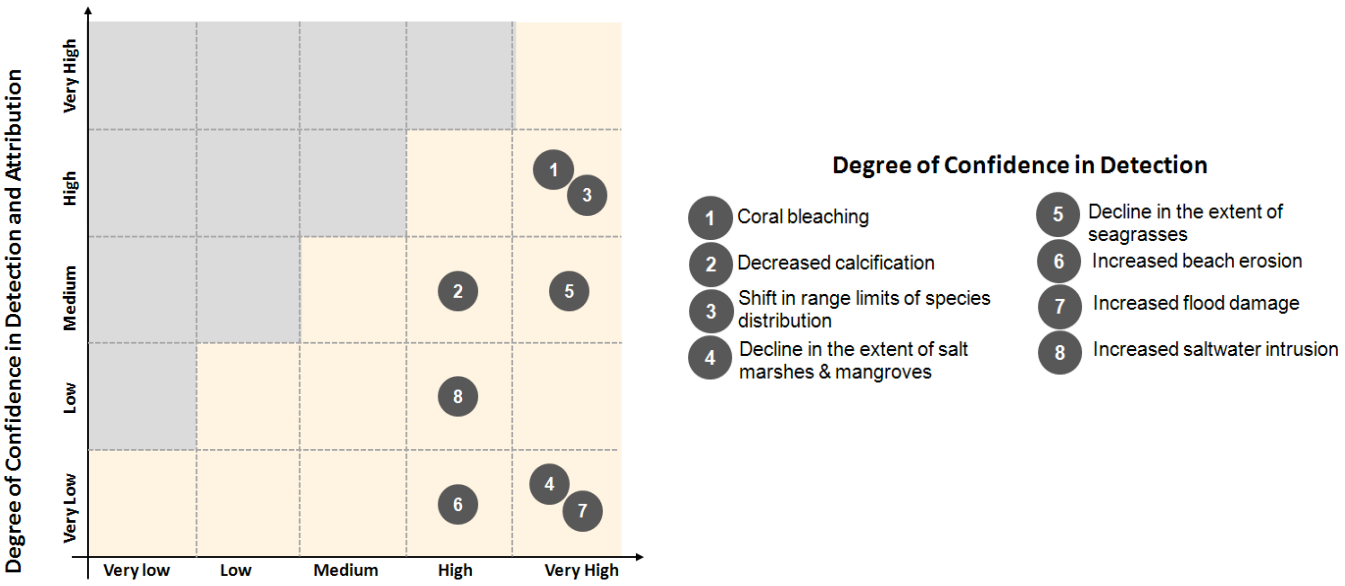

Figure 5-5: Summary on detection and attribution in this chapter.

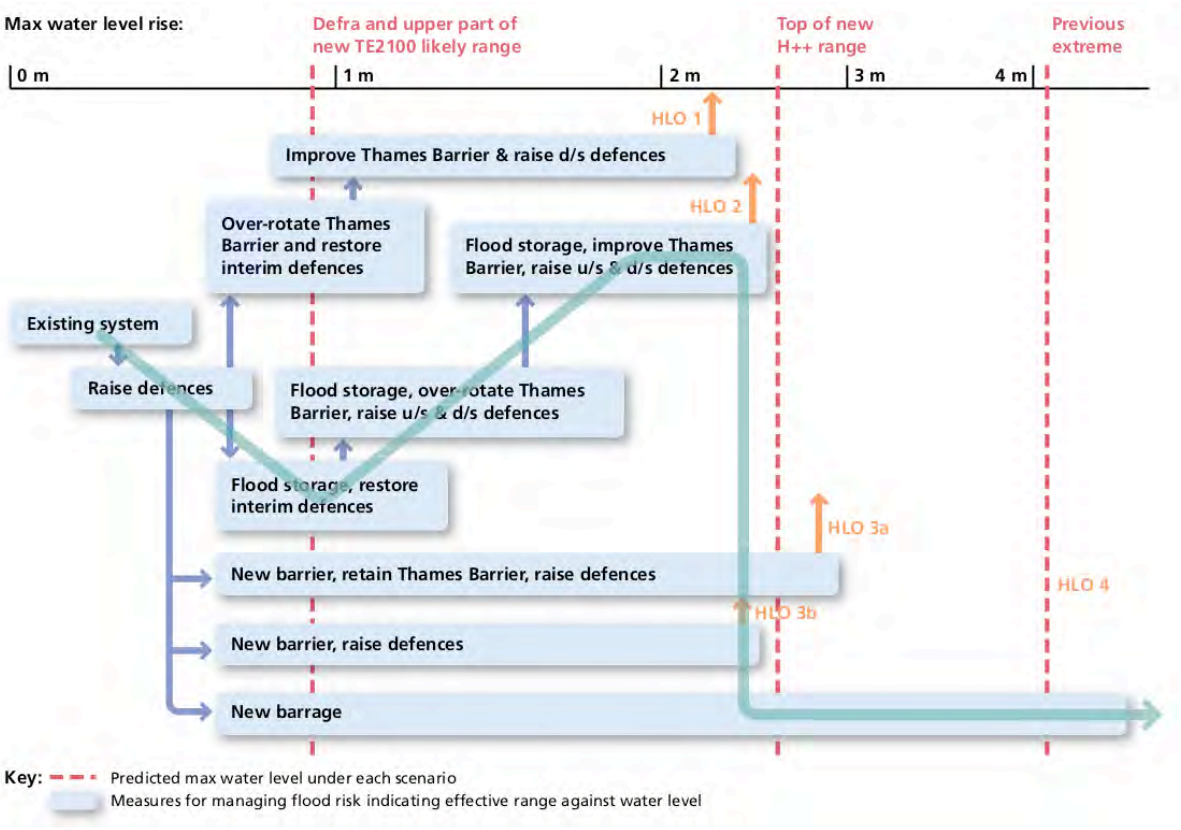

Figure 5-6: Adaptation measures and pathways considered in the TE2100 project. The boxed show the measures and extend over the range of sea level rise they are effective. The blue arrows link to alternative measures that may be applied once a measures is no longer effective. The red lines show the various sea-level rise scenarios used in the analysis. The fat green line shows a possible future adaptation pathway in the unlikely event of extreme change (>4 m rise).

Figure 5-7: Overview of the Delta Committee National Recommendations. Source: Stive *et al.*, 2011.

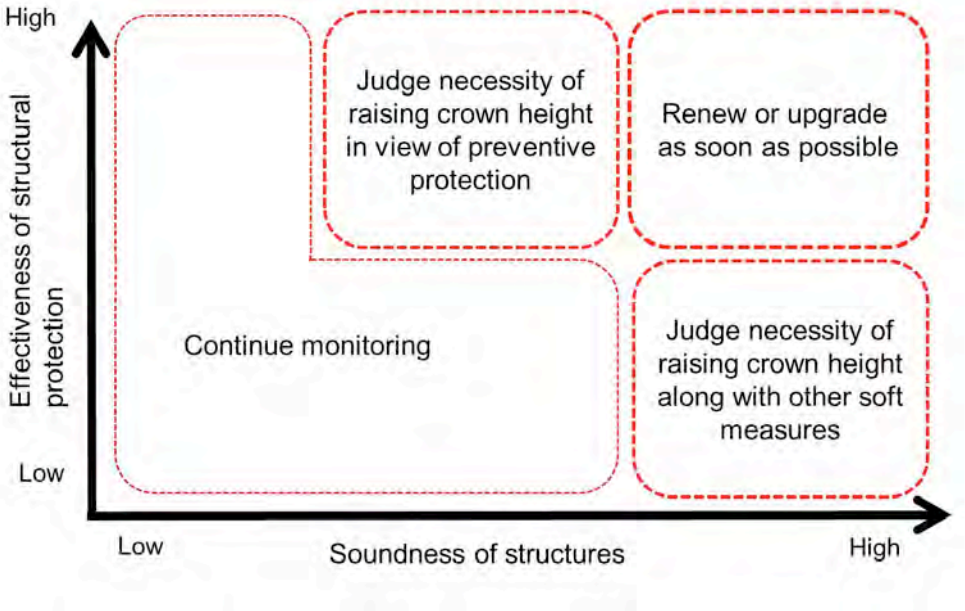

Figure 5-8: Priority in investment for adaptation to global warming.

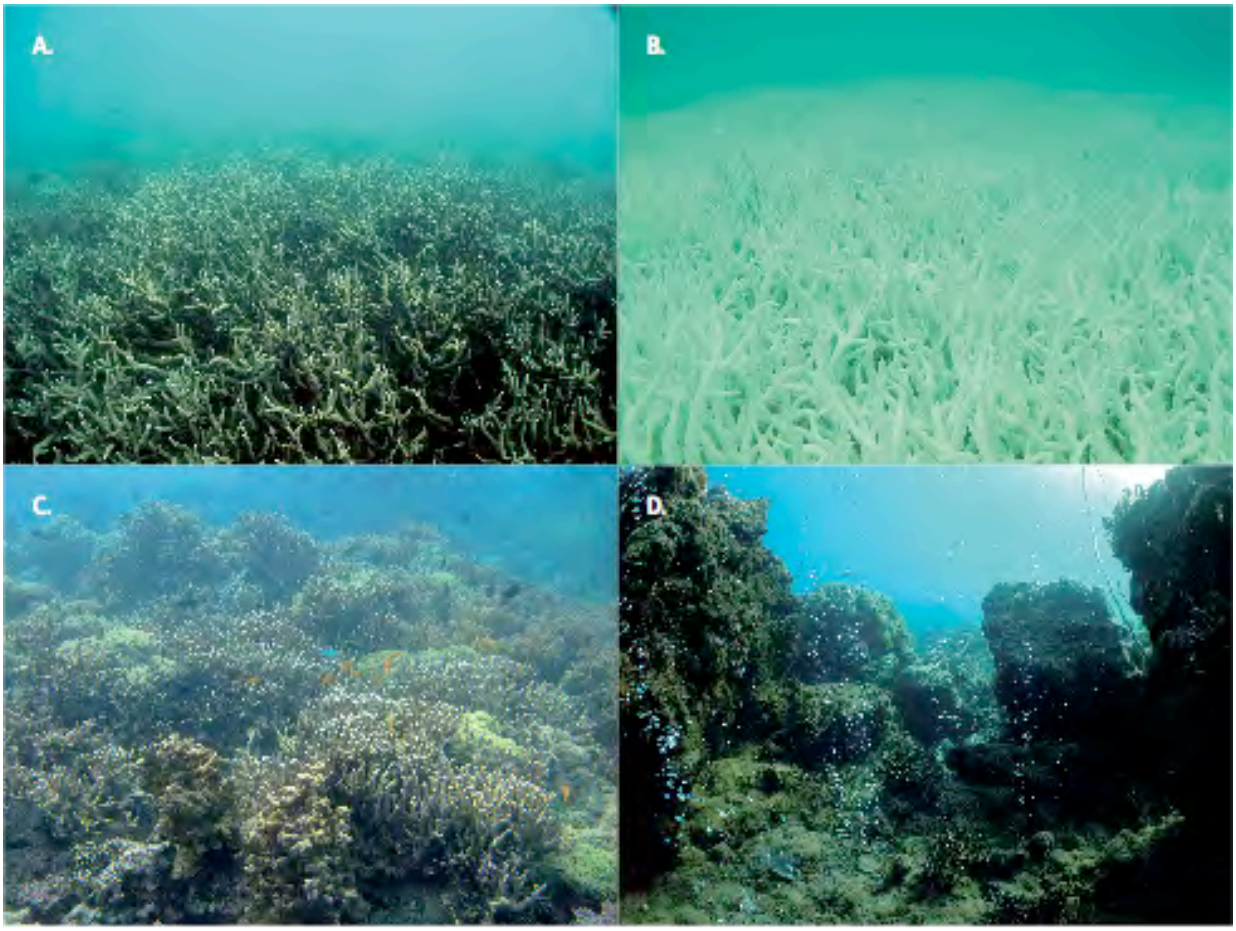

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

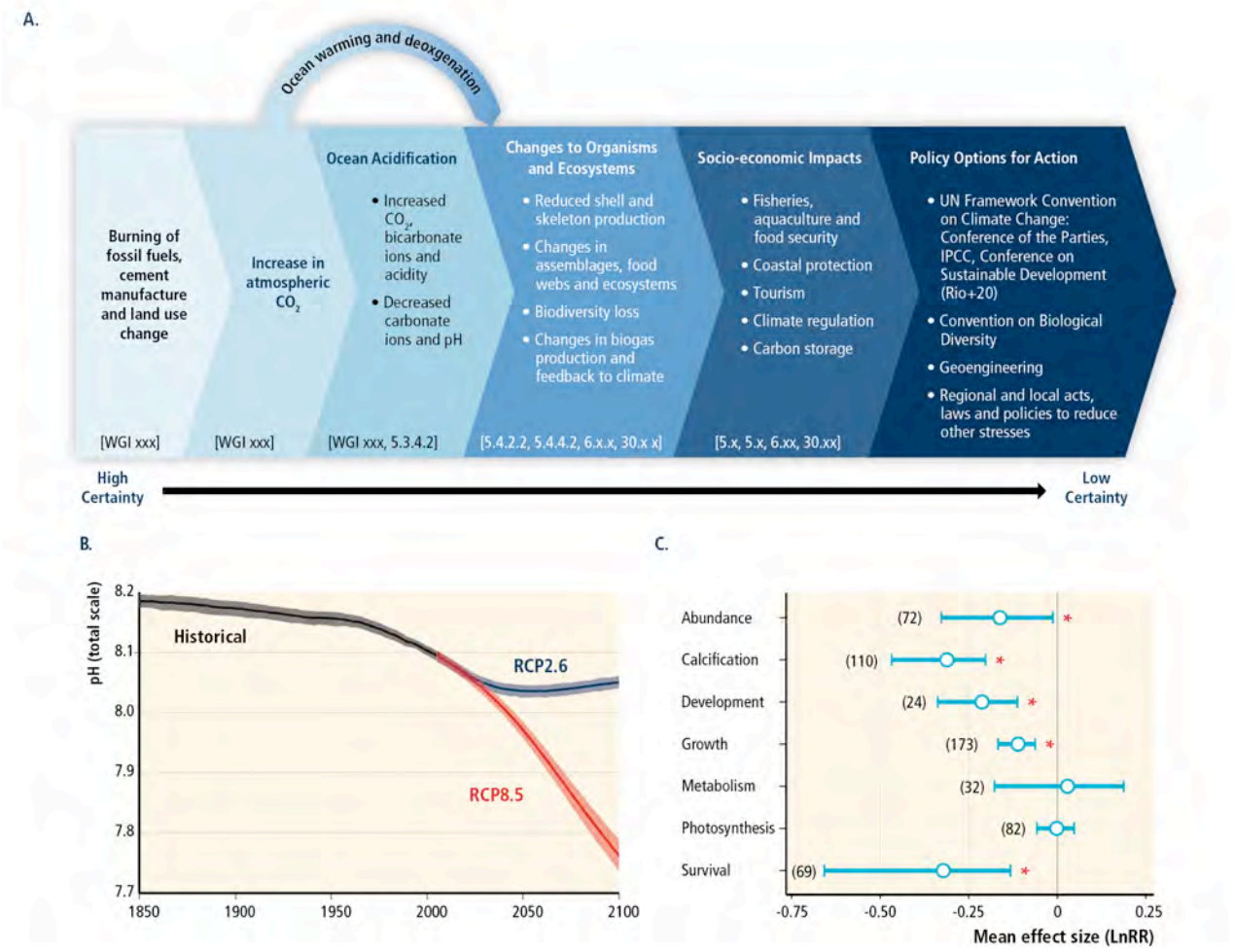

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

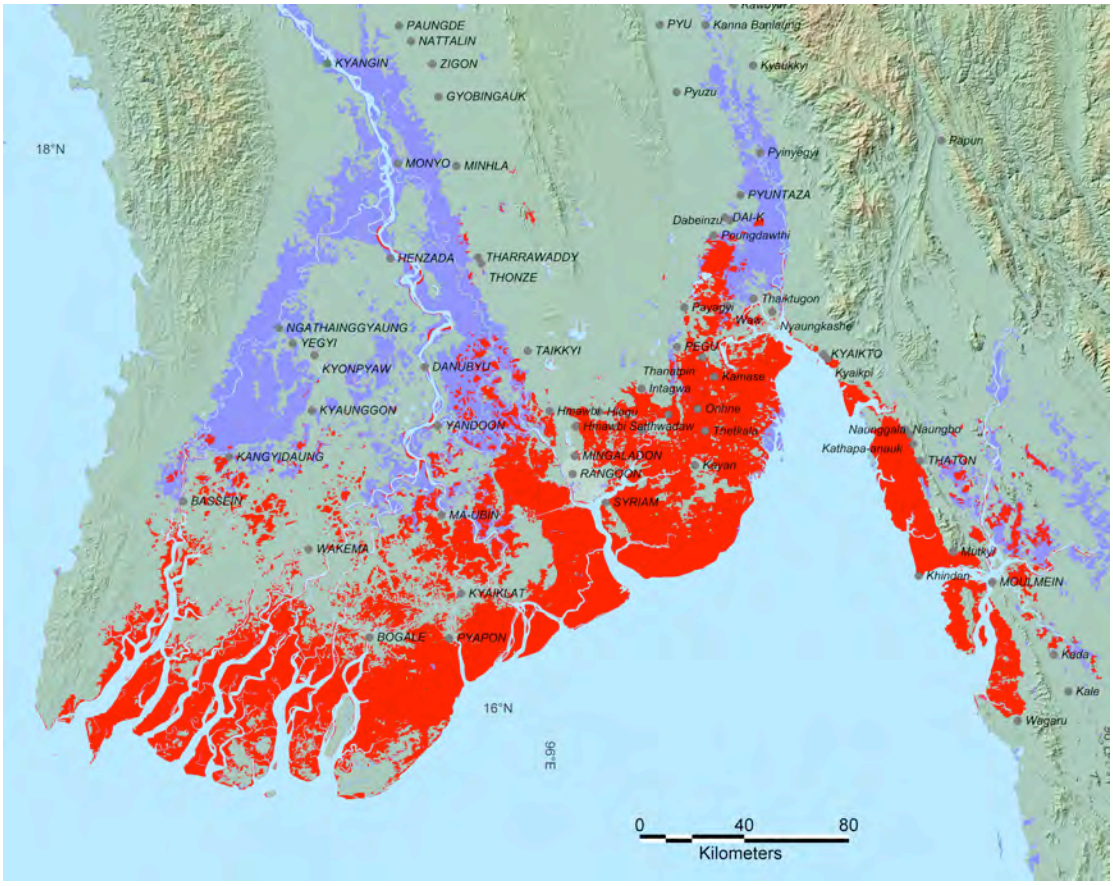

Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al.*, 2012).

Chapter 6. Ocean Systems

Coordinating Lead Authors
Hans-O. Pörtner (Germany), David Karl (USA)

Lead Authors
Philip Boyd (New Zealand), William Cheung (Canada), Salvador E. Lluch-Cota (Mexico), Yukihiro Nojiri (Japan), Daniela Schmidt (UK), Peter Zavialov (Russian Federation)

Contributing Authors
Jürgen Alheit (Germany), Javier Aristegui (Spain), Claire Armstrong (Norway), Gregory Beaugrand (France), Vsevolod Belkovich (Russian Federation), Chris Bowler (France), Peter Brewer (USA), Matthew Church (USA), Sarah Cooley (USA), Pablo Del-Monte (Mexico), Martin Edwards (UK), Michael Flint (Russian Federation), Mick Follows (USA), Thomas Frölicher (USA), Beth Fulton (Australia), Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Eileen Hofmann (USA), Andrew Knoll (USA), Lisa Levin (USA), Coleen Moloney (South Africa), Ian Perry (Canada), Elvira Poloczanska (Australia), J. Murray Roberts (UK), Björn Rost (Germany), Jorge Sarmiento (USA), Christian Wiencke (Germany), Astrid Wittmann (Germany)

Review Editors
Ken Drinkwater (Norway), Alexander Polonsky (Ukraine)

Volunteer Chapter Scientists
Lena Menzel (Germany), Astrid Wittmann (Germany)

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CC-CR. Coral Reefs
CC-OA. Ocean Acidification

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Executive Summary

Ocean ecosystems and their services will continue to respond to climate change (*high confidence*). Human societies benefit from and depend on ecosystem services, which are sensitive to climate change (*high confidence*), in particular the provisioning of food (fisheries and aquaculture) and other natural resources, nutrient recycling, climate regulation, protection from natural hazards, and aesthetic, cultural, and supporting services. [6.3.6, 6.4, 6.5]

Climate change is manifesting itself in the alteration of abiotic and biotic properties of the ocean (*high confidence*). Abiotic drivers changing in the ocean include circulation intensity, temperature, oxygen (O_2) and nutrient inventories, carbon dioxide (CO_2), ocean pH, salinity, and light regime. Biotic drivers range from the physiology of individual cells and organisms to ecosystem structure and function. [6.1.1, 6.2.2]

Marine ecosystems were and are being exposed to and affected by climate changes of different rates, magnitude and duration (*very high confidence*). In Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts (*high confidence*). The fossil record and present field and laboratory observations confirm key environmental drivers and responses of ocean ecosystems to climate change (*high confidence*), including migration, altered ecosystem composition, changes in abundance, and extinctions (*high confidence*). [6.1.2, 6.3]

The combination and often amplification of climate change drivers acting globally and additional human-induced local drivers such as overfishing, pollution, and eutrophication exacerbating hypoxia, result in enhanced vulnerability of natural and human systems to climate-related forcings presently and into the future (*high confidence*). Key observations and vulnerabilities are reflected in the progressive redistribution of species, changes in species' abundance and the reduction in marine biodiversity in sensitive regions and habitats, putting the sustained provision of ecosystem services and fisheries productivity at risk (*high confidence*). Socio-economic vulnerability is high particularly in tropical developing countries, progressively increasing the risk of reduced food supply, income and employment (*high confidence*). Key uncertainties include the up-scaling of climate change effects from organism to ecosystem level, the adaptive capacity of marine organisms and human societies to these impacts, the interactions with other human drivers, the sustenance of biogeochemical functions and productivity in the global ocean, and the effectiveness of climate mitigation and adaptation measures.

Physical effects of climate change on marine ecosystems may act, under some circumstances, as an additional pressure that cannot be mitigated by local conservation measures or a reduction in human activities like fishing (*high confidence*). Effects of climate change will thus complicate management regimes, e.g. presenting direct challenges to the objectives of spatial management once species undergo large-scale distributional shifts. This increases the vulnerabilities of marine ecosystems and fisheries. [6.4]

Understanding of physiology combined with field observations demonstrates that vulnerability of most organisms is defined by their specialization on specific, limited temperature ranges and accordingly, by their thermal sensitivity (*high confidence*). Temperature defines the geographical distribution of species and their responses to climate change (*medium confidence*). Temperature extremes act through losses in abundance and (e.g. sea ice and coastal) habitat, local extinction and latitudinal shifts (*very high confidence*). Vulnerability is greatest in polar animals due to narrow temperature ranges (*medium confidence*) and in e.g. tropical species living close to their upper thermal limits (*medium confidence*). Some warm water corals and their reefs will continue to respond to warming with species replacement, bleaching from loss of associated algae and a decreased coral cover resulting in habitat loss (*high confidence*). In general, knowledge of the mechanisms of climate effects helps to understand changes in the past, present and future. Genetic adaptation may occur; the capacity to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). [6.2.2-5, 6.3.2, 6.5.2]

Warming is causing shifts in the geographical distribution, abundance, and migration patterns of species, paralleled by a reduction in their body size and a shift in the timing of seasonal activities. This results in altered interactions between species including changes in competition and predator-prey dynamics (*high confidence*). There are many observations of poleward shifts in the distribution and abundance of fishes and invertebrates and/or of their shifts to deeper and cooler waters (*high confidence*). Poleward shifts of plankton have occurred up to 250 km per decade, up to 30 times faster than terrestrial species (*high confidence*). While marine turtles also experience direct effects of warming, birds and mammals are mostly indirectly impacted through sensitivities of their prey to these altered conditions (*high confidence*) [6.2.2, 6.2.5, 6.3., 6.5].

Modeling projects that, through species gains and losses correlated with warming, the diversity of animals and plants will increase at mid and high latitudes (*high confidence*) and fall at tropical latitudes (*low confidence*) [6.3.2, 6.5.2] leading to a large-scale redistribution of global catch potential for fishes and invertebrates (*medium confidence*). If a decrease in global ocean net primary production or a shift downwards in the size spectrum of primary producers occur, the overall fisheries catch potential will decrease, in ways influenced by other human impacts on ecosystem structure. Animal displacements are projected to lead to a 30–70% increase in the fisheries yield of high-latitude regions but a drop of 40%- 60% in the tropics by 2055 relative to 2005 under the SRES A1B scenario (*medium confidence* for the general trend of shifting fisheries yields, *low confidence* for the magnitude of change). [6.2.5, 6.3.2, 6.4, 6.5]

The oceans currently provide about half of global net primary production (NPP). Environmental controls on NPP include temperature, CO_2, nutrient supply and irradiance all of which are projected to be altered (WGI). The direction, magnitude and regional differences of a change of NPP in the open ocean as well as in coastal waters have *limited evidence* and *low agreement* for a global decrease projected by 2100. At high (polar) latitude an increase in NPP is also projected with *low confidence*. [6.3.1, 6.5.1]

Microbes (Bacteria, Archaea, unicellular algae and protozoans) serve key roles in marine ecosystems and sustain large scale processes and climatic feedbacks which will be altered by climate change (*medium confidence*). Identifying which microbial species or groups and processes are being affected by climate change and how these will be altered is presently based on *limited evidence* and *low agreement* as these organisms and their responses to environmental change are extremely diverse and often modulated by non-linear biological interactions or uncertain changes in circulation and nutrient supply. A warming ocean may enhance the metabolic rates of microbes, but also cause species specific phenotypic and genotypic responses, e.g. challenge their thermal tolerance and thereby, their abundance, distribution and community structure. Warming, more nutrient-rich coastal oceans may enhance the development of harmful algal blooms (*low confidence*) or pathogen distribution like cholera (*low confidence*). [6.2, 6.3, 6.4.2, 6.5]

Rising atmospheric CO_2 not only causes ocean warming but also changes in carbonate chemistry termed ocean acidification. Laboratory, mesocosm and field data show that ocean acidification has ramifications for processes ranging from physiology and behavior to population dynamics (*medium* to *high confidence*). Across organisms, sensitivity decreases with increasing capacity to compensate for the elevated internal CO_2 concentration or falling pH (*medium confidence*). Most plants including algae, respond positively to elevated CO_2 levels by increasing photosynthesis and growth (*high confidence*). A wide range of sensitivities to projected acidification

exists within and across organism phyla (*high confidence*). Laboratory work demonstrated a capacity to undergo trans-generational or evolutionary adaptation in some species, thereby reducing the impact of the projected change (*low* to *medium confidence*). Limits to adaptational capacity remain unexplored (*low confidence*). [6.2.2-6, 6.3.4]

Field observations attributed to anthropogenic ocean acidification are few due to limited changes in water chemistry between pre-industrial times and today. Shell thinning in planktonic foraminifera from various regions and Southern Ocean pteropoda has been attributed fully or in part to acidification trends (*medium confidence*). Coastward shifts in upwelling regimes of the Northeast-Pacific and upwelled CO_2-rich waters presently causing larval oyster fatalities in aquacultures (*high confidence*) or shifts from mussels to fleshy algae and barnacles (*medium confidence*) provide an early perspective on future effects of ocean acidification. Ecosystems at risk of ocean acidification are warm and cold water coral reefs (*high* or *medium confidence*). However, sensitivity is species specific; e.g. cold water corals display significant capacity to compensate for exposure to acidified seawater (*medium confidence*) in long-term laboratory cultures. [6.1.2, 6.2.2, 6.2.5, 6.3.4]

Several environmental drivers act simultaneously on ocean biota, often leading to interactive effects and complex responses (*high confidence*). For example, physiological knowledge projects that ocean acidification and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms like corals, coralline algae, molluscs, crustaceans and fishes (*high confidence*). Combined warming and ocean acidification reduce calcification in warm water corals (*high confidence*). [6.2.5, 6.3.2, 6.3.5, 6.5.2]

The ongoing expansion of hypoxic regions termed Oxygen Minimum Zones (OMZs) or anoxic "dead" zones constrains the habitat of O_2-dependent animals, plants and microbes while it benefits anaerobic microbial life (*high confidence*). Warming-induced stratification, reduced intensity of ocean circulation and the decomposition of organic matter by heterotrophic organisms create an expansion of these specialized, microbially dominated ecosystems, the regional OMZs (*high confidence*). The removal of fixed nitrogen (denitrification) via the metabolism of selected bacteria and archaea can reduce nutrient inventories and alter the N:P balance. Hypoxia tolerance varies among species and is influenced by temperature, elevated CO_2, food consumption, and O_2-demand (*high confidence*). [6.2.2-6, 6.3.3, 6.3.5]

Intensified ocean upwelling in some eastern boundary systems produce cooler surface waters associated with enhanced productivity (*medium confidence*), but in addition to hypoxia effects consequences for higher trophic levels in those areas remain unknown. [6.1.1, 6.3.3, 6.3.4, 6.3.6]

Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (e.g. purposeful nutrient fertilization, binding of CO_2 by enhanced alkalinity and direct CO_2 injection into the deep ocean) have very large associated environmental footprints (*high confidence*), with some actually requiring purposeful alteration of ocean ecosystems for implementation. Alternative methods focusing on solar radiation management (SRM) leave ocean acidification unabated. [6.4.2]

6.1. Introduction: Point of Departure, Observations, and Projections

The Oceans cover 71% of Earth's surface to an average depth of 3,800 m and represents more than 95% of the habitable environment (by volume) of our planet. Marine habitats exhibit natural variability on temporal scales from synoptic to interdecadal but the causes and ecological consequences are poorly understood as long-term series of direct observations from the open ocean are rare. The available information indicates that oceanic ecosystems are particularly sensitive to stresses mediated by climate change, partly because of direct effects on organisms and their interactions and partly because physical and chemical forcings control ocean temperatures, chemistry and the current regime, upper ocean stratification, nutrient supply and light regime and, hence, growth of phytoplankton, availability of food for heterotrophs (live organisms as prey, or their decomposing bodies, i.e. debris or dissolved organic matter) and the structure and function of the food webs. Physical and chemical attributes influence biogeochemical processes, including carbon cycle dynamics. They also shape the biological diversity the oceans support and the services they provide. Some of the knowledge on marine impacts has been assessed in the 4th IPCC assessment report, AR4 WGII Chs. 4-6, 15,16. For the first time in the series of IPCC reports, impacts on the oceans are a focus

in AR5, in the present sectoral chapter and a regional chapter (30). This allows for a more differentiated discussion of phenomena and impacts, as well as the associated uncertainties and the levels of confidence in observed and projected changes. For some of those, confidence has changed since AR4.

The present chapter focuses on the general principles and processes characterizing climate change impacts on the ocean system as a whole and its use by human society, so it focuses on global ocean processes rather than those in specific water columns or benthic provinces. It also addresses our understanding of functional mechanisms across all levels of biological organization, from molecular to organismal to ecosystem scale which is required for accurate projections of the ocean's responses to climate change. Division of the oceans into discrete functional units can help to elucidate variability and differences in ongoing and projected changes in key processes and carbon inventories across ocean regions (Figure 6-1). Oceanic ecosystems and the services that they provide must then be assessed on a region-specific basis (see WGII Chs 5, 28 and 30).

In order to assess the available evidence on the relationships between climate and ecosystem change, as well as to project future impacts, we rely on Representative Concentration Pathways (RCP) of climate change scenarios (Moss *et al*., 2010). We begin with a discussion of the variability of the principal physical and chemical parameters of the oceans and build on evidence available from paleo- and historical observations for identifying the forces causing change. Then, a conceptual framework of understanding climate change effects on organisms and ecosystems is developed and used to interpret empirical observations of ecosystem change, to assess the implications of such changes for ecosystem services and to identify plausible socioeconomic consequences.

[INSERT FIGURE 6-1 HERE
Figure 6-1: Productivity in 51 distinct global ocean biogeographical biomes as represented by a grid of thin black lines (after Longhurst, 1998), overlain with an average annual composite plot of chlorophyll *a* concentration, i.e., a proxy for phytoplankton stocks in the upper ocean, from the NASA/Orbimage SeaWiFs satellite (Bailey *et al*., 2006; McClain *et al*., 2004; McClain, 2009). The characteristics and boundaries of each biome are primarily set by the underlying regional physics and chemistry. Together, these provinces or biomes span several orders of magnitude in chlorophyll *a* from < 0.1 mg m^{-3} that characterize the low latitude oligotrophic regions (denoted by purple and blue) up to 10 mg m^{-3} in highly productive coastal upwelling regions in Eastern boundary currents (denoted by red).]

6.1.1. Recent Trends and Projections of Physical and Chemical Parameters

Trends in ocean conditions over the last 50 years reflect significant human impacts beyond natural variability on e.g. temperature or salinity or carbon content of the upper ocean (Pierce *et al*., 2012; WGI Ch.10).

6.1.1.1. Warming

Over the last 43 years average warming has occurred by >0.1 °C/decade in the upper 75 m and by 0.017 °C/decade at 700m depth (WGI Ch. 3), with trends strongest at high latitudes and regional differences between warming rates associated with prominent spatio-temporal structures (WGI Ch. 2) and scales of natural sea surface temperature variability (Figure 6-2), particularly strong at the typical ENSO high and low frequencies, and on multidecadal scales (>25 years). The interannual frequencies are dominant at most tropical oceans, while the multidecadal scale explains most of the high latitude variability. Changes in ENSO activity have been explored through global climate models, but trends in the spatial signature are highly uncertain. Moreover, global observation-based analyses of climate-induced changes in dominant variability frequencies are limited by data availability, especially for the low frequency scale at high latitudes, where the strongest warming is occurring. Temperature variations are accompanied by spatially variable changes in salinity. Both warming and freshening can cause enhanced stratification. Increases in salinity result from reduced precipitation relative to evaporation and have occurred in upper thermoclines of subtropical gyres at mid to low latitudes since 1970 (WGI Ch. 3). In contrast, freshening caused by enhanced precipitation relative to evaporation occurs at higher latitudes, exacerbated by increased sea ice melt. These trends are projected to continue into the 21st century (WGI Figure 12-34), leading to lower salinity intermediate waters sinking at high latitudes (Helm *et al*., 2010; WGI Ch. 3).

[INSERT FIGURE 6-2 HERE
Figure 6-2: Sea surface temperature variability in the last century (1911 to 2011). The top left map shows the sea surface temperature average for the period. The top right map illustrates the temperature range calculated as the difference between the maximum and minimum values for each grid component during the century. The spatial distribution of variability by time scales (left hand map series) was computed by accumulating the relative spectral densities of each 2°x2° grid box frequency-transformed series by frequency windows, corresponding to the multidecadal (period >25 years), bidecadal (15 to 25 years), decadal (8 to 15 years), low ENSO (El Niño Southern Oscillation) frequency (5 to 8 years), high ENSO frequency (3 to 5 years) and very high frequency (2 to 3 years) scales. The sum of the six maps at every single box corresponds to 100% of the interannual time series variability. The right hand histograms show the area of the World Ocean (%) at each weight interval, for each frequency window. All computations are based on the Extended Reynolds Sea Surface Temperature (NOAA, 2012).]

6.1.1.2. Acidification

Scenarios of future atmospheric carbon dioxide (CO_2) concentrations (given as partial pressures, pCO_2, in µatm) have been described by SRES and following several RCPs (Moss *et al.*, 2010; Meinshausen *et al.*, 2011). All RCPs lead to atmospheric pCO_2 levels somewhat less than 500 µatm by 2050. Then, under different RCPs, values between 420 µatm and 940 µatm can be expected by 2100.-On average, rising CO_2 concentrations in air cause significant increases in upper ocean CO_2 levels associated with oceanic drawdown of atmospheric CO_2 (Watson *et al.*, 2009). This leads to ocean acidification (OA), an increase in acidity measured as a decline in pH. OA also results in a progressive decrease of carbonate ion (CO_3^{2-}) concentration and thus of the saturation state (Ω) of calcium carbonates ($CaCO_3$; Zeebe and Westbroek, 2003; WGI Chs. 3, 6). Hence, the solubilities of calcite, Mg-calcite, or aragonite increase. These minerals are important components of shells or skeletons in many marine organisms (6.2.2). OA occurs on a background of natural variability of pH and Ω values over time and between sites from pH 8.2 in highly productive pelagic regions to 7.2 in mid-water layers where excess respiration causes low oxygen (O_2) and elevated CO_2 levels. While the physical and chemical basis of ocean acidification is well understood, few field data exist of sufficient duration, resolution and accuracy to document the acidification rate and its geographic and temporal variability (WGI Figure 3-17). Trends in anthropogenic OA clearly deviate from the envelope of natural variability (Friedrich *et al.*, 2012). OA presently ranges between -0.0015 and -0.0024 pH units per year (WGI Ch. 3, 6, 12; Dore *et al.*, 2009); average surface ocean pH has decreased by more than 0.1 units below the pre-industrial average of 8.17 and is expected to drop until 2100 by -0.13, -0.22, -0.28 to -0.42 pH units, at CO_2 levels of 421, 538, 670, and 936 ppm under the RCP 2.6, 4.5, 6.0 and 8.5 scenarios, respectively (WGI Figure 6-28). The rate of acidification varies regionally and is 50% higher in the Northern North Atlantic than in the subtropical Atlantic (Olafsson, 2009). Ice melt or excess precipitation cause salinity reductions (Jacobs and Giulivi, 2010; Vélez-Belchí *et al.*, 2010) and, thereby, an exacerbation of OA (Steinacher *et al.*, 2009; Denman *et al.*, 2011). In the absence of biota (6.2.2., 6.3.3), the changes in ocean chemistry due to OA will take thousands of years to be buffered through neutralization by calcium carbonate from sediments and tens to hundreds of thousands of years for the weathering of rocks on land to eventually restore ocean pH completely (Archer *et al.*, 2009).

6.1.1.3. Hypoxia

Oceanic O_2 concentrations range from over 500 µmoles kg^{-1} in productive, nutrient rich Antarctic waters (up to 140% saturation relative to equilibrium with the atmosphere; Carrillo *et al.*, 2004) to zero in coastal sediments rich in organic matter and in anoxic deep layers of isolated water bodies such as the Black Sea and the Cariaco Basin. The average value for the ocean is estimated as 178 µmol kg^{-1} (Sarmiento and Gruber, 2006). Large-scale fluctuations of O_2 concentrations have occurred over geological time (Wignall, 2001; Meyer and Kump, 2008), during glacial-interglacial cycles (Schmiedl and Mackensen, 2006; Robinson *et al.*, 2007), on multi-decadal (Yasuda *et al.*, 2006; Whitney *et al.*, 2007) inter-decadal (Arntz *et al.*, 2006), seasonal, synoptic and, in some high productivity regions, diurnal time scales (Grantham *et al.*, 2004; Connolly *et al.*, 2010). In ecological literature, the term hypoxia (see 6.3.3) is commonly used for O_2 concentrations below 60 µmoles kg^{-1}, according to the transition to communities with characteristic hypoxia adaptations. (It should be noted, however, that O_2 can become limiting to animal life once it falls from air saturation to levels well above this threshold (6.2.5) These hypoxic waters presently

occupy ~5% of the ocean volume ($7.6x10^{16}$ m^3) (Deutsch *et al*., 2011). Oxygen minimum zones (OMZs) associated with hypoxia at $O_2 < 22$ µmol kg^{-1} (< 0.5 ml L^{-1}) occupy nearly $30x10^6$ km^2 ($10.2x10^7$ km^3) in the open ocean (Paulmier and Ruiz-Pino, 2009) and cover about $1.15x10^6$ km^2 of the continental margin seabed (Helly and Levin, 2004; Diaz and Rosenberg, 2008). At the oxic-anoxic interface, suboxic waters with very low O_2 concentrations (< 4.5 µmoles kg^{-1}) occupy $4.6x10^{14}$ m^3 (less than 0.05 % of the ocean volume), mainly in the Northeast Pacific (Karstensen *et al*., 2008).

Hypoxia in midwater OMZs stretching over hundreds up to thousands of meters in the main ocean basis, and other O_2 deficient habitats is caused by respiration coinciding with CO_2 accumulation. Over the past 50 years, the mean rate of O_2 decrease was from 0.1 to over 0.3 µmoles kg^{-1} $year^{-1}$ (Stramma *et al.*, 2008; Stramma *et al.*, 2010), but in some OMZs it was much higher, due to warming, stratification and bacterial O_2 demand (WGI Box 6.5, Figure 1). Long-term declines in O_2 by about 7 µmoles kg^{-1} $decade^{-1}$ have been documented at mid water depths over much of the subarctic North Pacific (Keeling *et al.*, 2010). The number of extremely hypoxic coastal regions excluding metazoans, termed 'dead zones' and attributed to eutrophication induced deoxygenation, have increased from 120 in the 1980s to over 400 in 2008 (Diaz and Rosenberg, 2008). A rapid build-up of anoxic zones (void of O_2) has been found in stratified inland water bodies such as the brackish water Aral Sea (Zavialov, 2005; Zavialov *et al.*, 2009). With future warming, the spread of hypoxic zones will *very likely* accelerate, especially in temperate to subpolar regions where increases in ocean stratification due to warming or freshening of the surface layer can reduce the depth of winter mixing and create dense waters in association with ice formation. Most models project a decrease of global ocean oxygen content of 1 to 7 % by 2100 (Keeling *et al.*, 2010; WGI Figure 6-29 under RCP 8.5) implying feedbacks on the volumes of severely hypoxic and suboxic waters as well as key biogeochemical pathways (Deutsch *et al*., 2011). Fluvial runoff into the ocean causing eutrophication and associated hypoxia is projected to increase by 2100 due to climate-related intensification of the global water cycle (e.g. Milly *et al.*, 2008; Ch. 5.2.2.1.7). Figures vary for regions and catchment areas (Kundzewicz *et al.*, 2005). The evolution of low O_2 zones will also be linked to changes to the wind regime (e.g. Vecchi and Soden, 2007; Ren, 2010) and of the intensity, duration and seasonal timing of upwelling events (Snyder *et al*., 2003). The potential contribution of destabilized gas hydrates and bacterial methane oxidation to exacerbating hypoxia and acidification at high latitudes remains to be explored (Westbrook *et al*., 2009).

6.1.1.4. Other Physical and Chemical Drivers

Most modeling experiments indicate that the depth of the surface mixed layer will become shallower in the coming decades (e.g. Sarmiento *et al.*, 1998; Matear and Hirst, 1999) due to increased and seasonally extended (Holt *et al*., 2010) density stratification of the ocean especially in the tropics, the North Atlantic, the Northeast Pacific, and the Arctic (Capotondi *et al*., 2012). This may lead to decreased vertical transport of nutrients to surface waters (Polovina *et al.*, 2008; Doney, 2010). The resulting reduction in nutrient supply to phytoplankton growth may be partly compensated for by river plumes (Signorini *et al*., 1999), or by nutrient accumulation in the pycnocline as in the North Pacific (Whitney, 2011), or enhanced upwelling (Ch. 5.2.2.1.6) indicated by observations in the Peruvian (Gutiérrez *et al.*, 2011), Californian (Snyder *et al*., 2003; Rykaczewski and Dunne, 2010) and Canary systems (McGregor *et al*., 2007). However, upwelling rates projected by climate models largely diverge (Bakun *et al*., 2010).

6.1.1.5. Conclusions

It is *virtually certain* that with climate change, marine ecosystems are exposed to changing regimes of drivers, e.g. rising temperature, ocean acidification and the expansion of hypoxic zones. Warming of the surface layers *very likely* enhances and prolongs stratification, thereby limiting the nutrient inventory available to phytoplankton. Enhanced upwelling and human-induced eutrophication could partly compensate for the projected reduced nutrient supply in coastal oceans (*limited evidence, medium agreement*). Light availability to phytoplankton will *likely* increase due to shoaling of the surface mixed layer.

6.1.2. Paleo-Records

Paleontological records in marine sediments, from all ages and latitudes, provide information on spatial distributions of organisms and their abundance over time that can be readily related to the concurrent shifts in multiple environmental properties that are also recorded in these sediments. These records give us insights into extinctions, emergences, and changes in abundance and the environmental forcings that organisms are responding to. Temporal trends reveal influences of temperature, hypoxia and food availability on organisms and ecosystems, and changes in seasonal timing (phenology) of different components of the ecosystem (6.1.1, Figure 6-11). Spatial trends, from cores from different geographical locations, provide evidence of expansion of geographical ranges of plankton. These records are complemented by historical data sets of the last centuries of organisms which live for decades or centuries recording natural variability in the ocean system (WGI Ch. 3).

While the geological record often does not allow identification or direct attribution to a single driver of change or their relative importance, it supports by itself future projections on possible changes of a specific driver in extant ecosystems and their services only with *low* levels of *confidence* (6.4). Importantly though, increasing atmospheric CO_2 is causing warming in the surface ocean, altered/enhanced upper ocean stratification and consequently a decrease in dissolved O_2 concentration in the geological past and in the future. Thus, paleo and present day climatic shifts both share the same combination and sign of environmental changes (WGI). Therefore, a combination of data from the geological record and global circulation and carbon cycles models can use coupled warming and ocean acidification and deoxygenation events from the geological past to inform, with *medium confidence*, about future climate change impacts on ocean biota.

[INSERT FIGURE 6-3 HERE
Figure 6-3: Atmospheric CO_2 (bottom, grey) and temperature (middle, red/orange) changes with associated biotic changes (top) for the Paleocene Eocene Thermal Maximum (PETM) and the industrial era. Episodes of largest environmental change are indicated with yellow bars. CO_2 data are based on measurements at Mauna Loa (modern: Keeling *et al.*, 2005) and model output (PETM: Ridgwell and Schmidt, 2010; Zeebe *et al*., 2009). Temperature data are based on proxy data (modern: Wilson *et al.*, 2006; Lea *et al.*, 2003; PETM: Kennett and Stott, 1991) representing the regional temperature changes in the surface ocean. Modern biotic responses include changes in coralline algal growth (Halfar *et al.*, 2011), and coral calcification (De'ath *et al.*, 2009). Evolutionary changes are exemplified by the extinction of benthic foraminifera (Thomas, 2003). Abundance data (top row) of planktonic foraminifera and coccolithophores (modern: Field *et al.*, 2006; PETM: Bralower, 2002) indicate range expansion due to warming.]

The last glacial-interglacial transition is associated with an increase in atmospheric CO_2 of ~0.02 µatm/year on average over the transition (WGI Ch. 5) and hence fifty-fold slower than the current increase by 1 µatm/year on average over the last 100 years. Consequently, the resultant pH change of 0.002 pH units per 100 years during the glacial interglacial transition is small relative to the ongoing anthropogenic perturbation of >0.1 pH unit/century. Overall the glacial ocean was colder, with strong regional differences (WGI Ch. 5) and more O_2 rich than today's ocean. There is *high confidence* that foraminifera, coccolithophores, diatoms, dinoflagellates and radiolarians showed marked poleward range expansion during the last glacial-interglacial transition and abrupt short-lived events such as the Bølling-Allerød Warming (see WGI Ch. 5) (CLIMAP Project Members, 1976; MARGO Project Members, 2009). Lower CO_2 concentrations in the upper ocean during the glacial interval are associated with increased calcification in planktonic foraminifera (*limited evidence, medium agreement)*. In the Santa Barbara basin, changes in oxygenation did not cause extinctions in the benthic foraminifera (Cannariato *et al*., 1999) while in the Arabian Sea, a stronger monsoon and the associated increases in upwelling, productivity and local reduction in O_2 led to a loss in diversity in the benthic foraminiferal assemblages (Schmiedl and Leuschner, 2005).

The last time atmospheric CO_2 was close to today's was during the Pliocene warm period (3.3 to 3.0 Ma), with atmospheric CO_2 levels between 330-400 µatm (=ppm, Pagani *et al.*, 2010; Seki *et al.*, 2010) and temperatures ~+2 warmer than today (Haywood *et al.*, 2009, WGI Ch. 5) (*medium confidence*). Such a warming trend, occurring over several tens of thousands of years in contrast to 100 years projected for modern climate change, resulted in a poleward geographical expansion of tropical calcifying plankton species (Dowsett, 2007) (*high confidence*); however, no increases in species extinction or emergences compared to background rates has been associated with

Pliocene warming for coccolithophores (Bown *et al.*, 2004), corals (Jackson and Johnson, 2000) or molluscs (Vermeij and Petuch, 1986).

Perhaps the best analogue for the alteration of the future ocean is the Paleocene-Eocene Thermal Maximum (PETM), 55 million years ago (Ma), an event of rapid warming and ocean acidification, though model simulations for the future show 10 times higher rates of CO_2 input and hence ocean acidification in surface waters today than during the PETM (Ridgwell and Schmidt, 2010) (*medium confidence*). Depending on the assumed rate and magnitude of the CO_2 release during the PETM, models project a 0.25 to 0.45 pH unit decline in surface waters (Ridgwell and Schmidt, 2010) and a reduction in surface ocean aragonite saturation from Ω=3 to Ω=2 or even as low as 1.5. During the PETM, warming caused range expansion of warm-water taxa towards higher latitudes (*high confidence)*. While the composition of coccolithophore (Gibbs *et al.*, 2006, 2013) and dinoflagellate assemblages (Sluijs and Brinkhuis, 2009) changed, suggested to reflect the changes in nutrient availability and/or warming (6.2.2.-3), there was no bias in extinction towards more heavily calcifying species. In contrast, the benthic ecosystem recorded a 50% extinction among benthic foraminifera (Thomas, 2007) and a major change in the macrobenthic community (Rodríguez-Tovar *et al.*, 2011). In contrast to sediment dwellers, pelagic crustaceans (ostracods) did not show any significant change in species composition (Webb *et al.*, 2009). In shallow coastal waters, calcareous algae and corals were replaced by larger benthic foraminifera (Scheibner and Speijer, 2008) (*medium confidence*). Models for the PETM suggest that the increase in oceanic vertical temperature gradients and stratification led to decreased surface ocean productivity and O_2 depletion in the deep sea (Winguth *et al.*, 2012), particularly in the equatorial zone by weakening of the trade winds and hence reducing upwelling.

The very warm climates of the Mesozoic (251 to 65 Ma) led to a number of oceanic anoxic events (Jenkyns, 2010). For some of these events, anoxia was not restricted to the deep ocean but vertically expanded OMZs led to photic zone anoxia (Pancost *et al.*, 2004). Some of these Cretaceous oceanic anoxic events were associated with extinctions or increased turnover (normalized sum of originations and extinctions) of the marine plankton (an average of 30% for planktonic foraminifera and radiolarians) although the changes were very small for other groups of organisms, e.g. coccolithophores (maximum 7%, Leckie *et al.*, 2002). The causal link between O_2 reduction and the evolutionary change in these groups is tenuous as these events were also associated with warming, changes in nutrient supply and, possibly, ocean acidification (Hönisch *et al*., 2012).

For examples of marine ecosystem collapse at global scale, expansion into the deep record of the past 250 million years (Myr) is required. Some mass extinctions, and in particular the Permian Period extinction 251 Ma ago, have been associated with large scale inputs of carbon into ocean and atmosphere and the associated deep-sea O_2 decline and global warming (Knoll *et al.*, 2007; Kiessling and Simpson, 2011; Knoll and Fischer, 2011) with consequent warming, acidification and O_2 depletion, though the rate of change has not been accurately constrained to date for any of these events. The end Permian mass extinction preferentially affected reef organisms such as corals and sponges resulting in a 4 Myr period without reef builders (Kiessling and Simpson, 2011). The extinction rate of the end-Permian biological collapse was greater than any projection for coming centuries (Bambach, 2006), but it underscores the differing vulnerabilities of marine life to environmental perturbation among organisms of differing anatomy, physiology and ecology (Knoll and Fischer, 2011).

Of the last 100 Myr, only the last 2 Myr had CO_2 at levels lower than any projected for this decade and only the deep time older than 33 Ma record has CO_2 levels comparable to business as usual projections for the end of 2100 (WGI Ch. 5; Hönisch *et al*., 2012). That marine biota thrived throughout most of this era could imply that the organisms, which make up marine ecosystems, will not be impaired in a future warm, high CO_2 world. However, such comparisons are invalid because the key environmental issue of the 21st century is one of an unprecedented rate of change in CO_2 levels, not simply magnitude (Hönisch *et al*., 2012). The unparalleled rate and magnitude of modern ocean acidification in at least the last ~300 Myr of Earth history highlights the magnitude and scale of the current change in several environmental drivers. The slower events in the geological history provide *robust evidence and high agreement* of environmentally-mediated compositional changes in fauna and flora and, in some cases, of extinction and, to much lesser degree, emergences. Although similarities exist, no past natural climatic event perfectly parallels future projections, emphasizing how unprecedented future climate change is in the evolutionary history of most organisms. In light of the present rate of change the challenges involved may therefore be outside the adaptive capacity of many organisms living in today's ocean (*low to medium confidence*).

6.1.3. Long-Term Biological Observations

Ocean ecosystems are complex, time and space variable, and non-steady state (Figures 6-4, 6-5). While climate science has benefitted from paleo-observations of tree rings, sedimentary records and ice cores (6.1.2), data sets of oceanic phenomena are rare. Those existing (Table 6-1) provide evidence that spatial and temporal variability are inextricably linked (Stommel, 1963). Therefore, systematic, long-term interdisciplinary observations using repeated, highly calibrated measurements at a given field site are required to distinguish natural ecosystem variability from (long-term) anthropogenic trends. The undersampling of ocean phenomena in time (Henson *et al*., 2010) and space constrains meaningful assessments of current states and projections about future ones.

[INSERT TABLE 6-1 HERE
Table 6-1: Selected examples of long-term biological and ecological observations in the oceans (NPP denotes Net Primary Productivity).

[INSERT FIGURE 6-4 HERE
Figure 6-4: Multiple coupled temporal and spatial scales of variability in physical, physiological and ecological processes in marine systems. Observations over broad time and space scales are necessary to separate natural variability from human-induced impacts, and define appropriate observation tools. The shaded regions depict the approximate boundaries of major processes, and the boxes define the scales of selected measurement/ observation procedures. Langmuir cells are a series of wind-driven shallow, slow, counter-rotating circulations at the ocean's surface. From Karl (2010), as modified from Dickey (1991).]

Historical data sets of organisms with life histories of decades and centuries and high resolution sediment cores covering the last few centuries document the responses of biota to natural variability in the ocean system (such as the North Atlantic Oscillation Index [NAO], the Atlantic Multidecadal Oscillation [AMO], the Arctic Climate Regime Index [ACRI], Pacific Decadal Oscillation [PDO] or the El Niño-Southern Oscillation [ENSO]) but also to warming of the surface ocean since the 1970s (6.3.2). Many examples highlight the influences of temperature, hypoxia and abundance of food on organisms and ecosystems, causing, for example, changes in biodiversity, expansion of geographical ranges of plankton, changes in seasonal timing (phenology) of different components of the ecosystem and changes in macrobenthos calcification (6.2, 6.3; Figures 6-3, 6-5).

[INSERT FIGURE 6-5 HERE
Figure 6-5: Time-series of water column integrated primary production (PP) anomalies at: Northwestern Spain, La Coruña (43° 25.2 N, 8° 26.4 E); HOT (22° 45 N, 158°W); BATS (31° 50 N, 64° 10 W); Monterey Bay, Central California Current (37°N, 122°W); Cariaco Basin, Venezuela (10°30 N, 64°40 W), reproduced from Chavez *et al.* (2011). Anomalies were calculated by integrating over the water column, then interpolating to 14 d, smoothing with a moving average and differencing for each 14-d interval from the grand mean for that interval. All sites except Cariaco seem to show positive (pink) PP anomalies after 2000.]

The research questions presently addressed using long-term data sets range from changing species composition and phenology via investigations of physical and chemical drivers causing these changes to low-frequency events, e.g. regime shifts (abrupt, non-linear and persistent changes in the structure and function of a system, Table 6-1). National programs run by marine stations sampling regional seas provide detailed long-term data sets augmented by several international limited-term scientific programs such as the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). The ship-based time-series programs in the North Pacific Subtropical Gyre (HOT), the Sargasso Sea (BATS), Ligurian Sea (DYFAMED), Canaries (ESTOC), southwest of Kerguelen Island (KERFIX), northwest of Hokkaido Island (KNOT) and southwest of Taiwan (SEATS) have provided invaluable data on the physical and biogeochemical state of the oceans (Karl *et al*., 2003). Data from these sites have documented decadal scale ecosystem changes, including ocean acidification (Dore *et al*., 2009; WGI Ch. 3). Additional trends will emerge as the time-series programs continue and new sites are added.

Direct observations are complemented by satellite remotely-sensed datasets, with ocean color data (e.g. SeaWiFS) providing estimates of chlorophyll concentrations, used as a proxy for phytoplankton stocks. Because total chlorophyll cannot be measured from space, the near surface chlorophyll (approximately one optical depth) is extrapolated to whole water-column chlorophyll. Large uncertainties persist in the interpretation as chlorophyll estimates from satellite reflect both phytoplankton stocks and their physiological status (Dierssen, 2010; Behrenfeld, 2011). In conjunction with algorithms these chlorophyll estimates are converted to Net Primary Production (NPP) (6.1.3., Saba *et al*., 2011). Behrenfeld *et al.* (2006) using SeaWiFs data, report a prolonged and sustained global NPP decrease of 190 Tg C per year for the period 1999 to 2005 - an annual reduction of ~0.4 % of global NPP. In contrast, a time-series of directly measured NPP between 1988 to 2007 by Saba *et al.* (2010) (i.e. *in situ* incubations using the radiotracer ^{14}C-bicarbonate) revealed an increase (2 % yr^{-1}) in NPP for two low latitude open ocean sites. This indicates uncertainties in either methodology and/or the extent to which discrete sites are representative of oceanic provinces (Saba *et al*., 2010, 2011). Furthermore, modeling studies have argued that the <20 year archive of SeaWiFS is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson et al., 2010).

6.2. Diversity of Ocean Ecosystems and their Sensitivities to Climate Change

6.2.1. Overview: Ocean Characteristics and Climate Sensitivities

Global scale observation and modeling studies provide evidence, with *high confidence*, of present and future climate-mediated alterations of the ocean environment (6.1.1., WGI Chs. 3, 6; Bopp *et al*., subm) which in turn leads to impacts on ocean ecosystems (Boyd and Doney 2002; Brierley and Kingsford, 2009; Hoegh-Guldberg and Bruno, 2010; Drinkwater *et al*., 2010; Overland *et al*., 2010). An assessment of present findings and projections requires knowledge of the characteristics of ocean biota and ecosystems and the background of their climate sensitivity.

Life on Earth is phylogenetically and metabolically diverse as a result of nearly 4 billion years of evolutionary history. Marine microorganisms are the oldest forms of life, and the most diverse while the more complex organisms are constrained to limited functional types (Table 6-2). As anthropogenic climate change accelerates, a key issue is how quickly organisms can adapt. Evolutionary adaptation is typically thought to depend upon the genetic variation present within a population, and the environment is believed to select the fittest genotypes from within it (Rando and Verstrepen, 2007; Reusch and Wood, 2007). The inherent variability of marine environments (6.1.1) is suggested to ensure that genetic variation within populations is maintained at high levels. However, there is limited information about genetic variation within species, except for a few well-studied species of fishes and bacteria. The capacity of any species to adapt is highly variable, depending on mutation rates, generation time, and whether population size is large enough to harbour sufficient variation. Processes based on DNA point mutations may be too slow to permit adaptation to rapid climate change (Bowler *et al*., 2010). The fitness of marine organisms may, however, also be influenced by epigenetic regulation mechanisms, such as reversible histone modifications and DNA methylation (Richards, 2006), which are transmitted from generation to generation. Such processes are suggested to be remarkably rapid in terrestrial ecosystems (Bossdorf *et al*., 2008). There is currently *limited evidence, medium agreement* and *low confidence* in evolutionary adaptation induced by climate change in recent centuries.

[INSERT TABLE 6-2 HERE
Table 6-2:Variations in metabolism based on sources of energy, electrons and carbon according to Karl (2007a), complemented by the taxa which exploit these pathways. Mode of metabolism may relate to organizational complexity and tolerance to environmental extremes (Figure 6-8).

Metabolic pathways and their rate of use according to energy demand respond to changing temperatures in virtually all cases or to changing irradiance and CO_2 levels, specifically exploited by the respective modes of metabolism. These responses may be involved in direct or indirect effects of climate change and associated drivers (6.1.1) on marine organisms and contribute to set limits to their adaptability (6.2.2).]

6.2.1.1. Pelagic Biomes and Ecosystems

Organisms living in the pelagic biomes are key to biogeochemical processes in the ocean. The fixation of CO_2 via photosynthesis, a process also known as primary production, forms the base of the marine foodweb. Photosynthesis in the surface ocean is controlled by light, temperature, inorganic nutrients (CO_2, nitrate, phosphate, silicate, trace elements including iron, and the temperature dependent formation rate, stability and duration of the surface mixed-layer depth (MLD) (6.1.1., Sverdrup, 1953; Taboada and Anadón, 2012). Temperature and its variability (Figure 6-2) thus are key factors governing the occurrence, diversity, development, reproduction, behaviour and phenology of marine organisms (Edwards and Richardson, 2004; Beaugrand *et al.*, 2009; Brierley and Kingsford, 2009, Tables 6-3, 6-4). The delivery of nutrients from deep water below the euphotic zone is controlled by vertical eddy diffusivity and advection, caused by the combined effects of local winds and thermohaline (density)-driven processes such as ocean circulation (Rykaczewski and Dunne, 2010) which create net upwelling (temperate, subpolar) and net downwelling (subtropical) gyres (Table 6-3). Coastal oceans are nutrient enriched by tidal mixing, estuarine circulation and upwelling. All of these processes are subject to climate-related influences and associated shifts in physical forcing. Changes in environmental conditions and the displacement of organisms by convection cause variability in phytoplankton productivity, competitiveness and natural selection (Margalef, 1978; Margalef *et al.*, 1979) and result in changes in carbon sequestration (Figures 6-1, 6-6). Reduced nutrient availability causes primary production to fall, leading to a reduction in the amount of energy supplied through the web to higher trophic levels, including fish and invertebrates (*high confidence*, Ware and Thomson, 2005; Brander, 2007), and defining fishery yields (Cheung *et al*., 2008; Friedland *et al*., 2012). Species replacement might result in a redirection of carbon and energy flows. The wide range of trophic structures in marine foodwebs and the potentially non-linear changes in energy transfer under different primary production and temperature scenarios (Stock and Dunne 2010) make it difficult to accurately predict how changes in primary production will alter higher trophic levels.

[INSERT TABLE 6-3 HERE
Table 6-3: Environmental forcing on biological production by physical, chemical and biological characteristics of major pelagic ecosystems (Adapted from Barber, 2001, based on the original analysis by McGowan, 1974).]

[INSERT FIGURE 6-6 HERE
Figure 6-6: A schematic representation of the ocean's biological pump, which responds to climate change and is a relevant conduit for carbon sequestration. It is difficult to project how the pump might be altered (Table 6-4) and whether it would represent a positive or negative feedback to climate change which causes: A, shifts in NPP (Net Primary Production; Bopp *et al*., 2002); B, floristic and faunistic shifts in the pelagic realm (Beaugrand *et al.*, 2009) that may alter the relationship between OA and ballasting of settling particles (Klaas and Archer, 2002); C, changes in proportion of NPP released as DOM (Dissolved Organic Matter) due to the effects of ocean acidification (Engel *et al.*, 2004); E, warming and faster bacterial enzymatic rates of particle solubilization (Christian and Karl, 1995); and faunistic shifts at depth (Jackson and Burd, 2001). Modified from Buesseler *et al.* (2008) by J. Cook (WHOI).]

[INSERT TABLE 6-4 HERE
Table 6-4: A wide range of processes make up the ocean’s biological pump (Figure 6-6). In order to assess how a changing climate will alter the functioning of the pump, and the resulting biogeochemical feedbacks on global climate, the cumulative effects of climate-change mediated alteration of processes from cellular to ocean basin, and from pelagic to mesopelagic, must be quantified. This table illustrates, using published information, the complexity of the integrated knowledge platform needed to provide evidence of these biogeochemical ramifications and thus the present limits to clear conclusions about climate induced effects on the biological pump (C, Carbon; TEP, Transparent Exopolymer Particle; DOM, Dissolved Organic Matter; POM, Particulate Organic Matter).]

6.2.1.2. Benthic Habitats and Ecosystems

Benthic communities are defined as those that live in, on, or in association with the sea floor. Benthic organisms are classified by their size (mega-, macro-, meio-, microbenthos), their mode of energy supply (Table 6-2) or their mode of food uptake (suspension feeders, deposit feeders, herbivores, carnivores). Their habitats range from the intertidal to the deep sea and are characterized by climate regime, water depth, light penetration, distance from land,

topography, substrate (rocky, hard, soft, mixed), sediment grain size and chemistry or by the dominant plant or animal communities that they support. In general, benthic organisms living in shallow waters or the intertidal (where they experience temporary exposure to air) are prone to experience and tolerate the influence of widely fluctuating environmental parameters due to natural or anthropogenic influences, such as temperature extremes, hypoxia, elevated CO_2 or fluctuating sea level including sea level rise (WGI Chs. 3, 12). As benthic systems comprise sessile or slow moving plants and animals, they may be adapted to local conditions. Many of them are unable to escape from unfavorable changes except by means of fertilized eggs or planktonic larvae. In the deep sea, where environmental conditions remain unchanged on large geographical scales, some meiobenthic deep-sea organisms may show extremely wide distribution ranges (Menzel *et al*., 2011; Gooday and Jorissen, 2012).

Benthic ecosystems are coupled to the pelagic realm via the biological pump (Figure 6-6), the chemical exchange of nutrients, gases and by the existence of pelagic and benthic life history stages. Even in abyssal benthic habitats there is a continuous rain of organic detritus and this serves as the primary source of carbon and energy for benthic communities. This inextricable connection to primary marine productivity means that climate impacts on surface marine ecosystems (as oceans stratify, warm and become more acidic) will impact the most remote benthic communities, even if direct changes to the physical habitat do not occur (Smith *et al.*, 2009).

Benthic habitats are influenced by ecosystem engineers (sensu Jones *et al.*, 1994) which can be grouped into two categories. Autogenic engineering species (like corals) form habitat from the structures they produce (e.g. coral skeletons) while allogenic engineering species form habitat through their behaviour (e.g. by mechanical displacement of sediment, a process termed bioturbation). Both types of ecosystem engineers have the potential to influence the regeneration of nutrients and to affect benthic-pelagic coupling. If climate change negatively affects the engineering species, the entire ecosystem may be impacted.

6.2.2. Mechanisms and Principles of Climate Change Impacts across Organism Taxa

This section focuses on the principles of climate impacts known across organism taxa, 6.2.3. to 6.2.6. then report the taxon-specific aspects. A comprehensive understanding of mechanisms responding to climate related environmental factors at ecosystem, whole organism, tissue, cell and molecular levels of biological organization would provide a solid foundation for reliable interpretation and attribution of climate change effects on ocean biology. The genetic and physiological underpinning of climate sensitivity of organisms sets the boundaries for ecosystem response and provides crucial information on sensitivities, resilience and the direction and scope of future change. Empirical studies of marine organism and ecosystem sensitivities have made progress in identifying the mechanisms and processes linking climate to ecosystem changes (Drinkwater *et al.*, 2010; Ottersen *et al.*, 2010). Changes in community composition, species interactions and the food web often build on organismal effects elicited by environmental forcing (e.g. Pörtner and Farrell, 2008; Boyd *et al*., 2010; Ottersen *et al.*, 2010). Knowledge of the underlying mechanisms in a hierarchy of organismal to molecular effects (Pörtner, 2002a, Pörtner and Knust, 2007; Raven et al., 2012), appears as a major asset for attributing observations to climate and for projections of impacts (Pörtner *et al.*, 2012). Knowledge of overarching similarities across organism domains, archaea, bacteria, and eukarya (Woese *et al*., 1990) or kingdoms (Cavalier-Smith, 2004) would facilitate projections of climate impacts. Microbes, i.e. bacteria and microalgae support many fundamental biogeochemical cycles and may respond by exploiting their large diversity, e.g. undergoing species replacements (Karl *et al*., 2001), and thereby sustaining their biogeochemical roles. Species replacements also occur among macroorganisms (plants and animals), however, for most of them their resilience, well-being, abundance, survival and conservation have been the research foci.

After identifying the principle effects of individual drivers across organism taxa understanding their integrated action is required for comprehending climate change effects (6.3.5). Furthermore, such effects may be compensated for on long time-scales by acclimation and evolutionary adaptation to individual or multiple drivers, as seen in the coccolithophore *Emiliania huxleyi* under high pCO_2 (1100 and 2200 µatm) over 500 asexual generations (Lohbeck *et al*., 2012). In macroorganisms the rate of evolutionary adaptation is constrained by their long generation times but is enhanced by large phenotypic variability among larvae as a pool for selections, with high mortality rates (e.g. Sunday *et al*., 2011). In general, the mechanisms setting limits to acclimation or adaptation capacity are presently unknown for virtually all climate drivers. However, mass extinctions occurring during much slower rates of climate

change in earth history (6.1.2) suggest that evolutionary rates in macroorganisms may not be fast enough to cope with various drivers changing. Interactions of drivers like ocean warming, acidification, hypoxia, freshening with each other and with other human-induced drivers like eutrophication are addressed in 6.3.5.

6.2.2.1. Principles of Temperature Effects

Thermal reaction norms describe the temperature dependent changes in performances such as growth and have been used to evaluate sensitivity (Figure 6-7). They apply across organism phyla (Chevin *et al.*, 2010), viruses (Knies *et al*., 2006), bacteria (Ratkowsky *et al*., 1983), phytoplankton (Eppley, 1972; Thomas *et al*., 2012), higher algae and plants (Bolton and Lüning, 1982; Müller *et al.*, 2009, 2011; Vitasse *et al*., 2010) and animals (Huey and Kingsolver, 1989; Deutsch *et al*., 2008; Angiletta, 2009). The shape and width of the curves can shift within limits and mirror the large scale distribution boundaries of a species or population. Maximum temperatures tolerated differ largely between organisms, depending on organizational complexity (Figure 6-8). The knowledge of the mechanisms shaping such curves and associated thermal limits appears most advanced in animals (Pörtner *et al*., 2012; 6.2.5) but these have not been systematically explored in other organism groups (e.g. Green *et al*., 2008).

[INSERT FIGURE 6-7 HERE
Figure 6-7: Mechanisms linking organism to ecosystem response explain the why, how, when and where of climate sensitivity (based on knowledge for animals, after Pörtner, 2001, 2002a, 2012; Pörtner and Farrell, 2008, blue to red colour gradients illustrate transition from cold to warm temperatures). (A) As all biota, animals specialize on limited temperature ranges, within which they grow, behave, reproduce, defend themselves by immune responses. Optimum temperatures (T_{opt}) indicate performance maxima, pejus temperatures (T_p) the limits to long-term tolerance, critical temperatures (T_c) the transition to anaerobic metabolism, and denaturation temperatures (T_d) the onset of cell damage. These OCLTT thresholds (see text) can shift by acclimatization (horizontal arrows). Under elevated CO_2 levels and in hypoxic waters performance levels can decrease and windows of performance be narrowed (dashed green arrows pointing to dashed black curves). (B) Thermal range widths (horizontal arrows) change between individual life stages of a species. (C) The shift of performance curves between polar, temperate and tropical animal species reflect evolutionary adaptation to the respective climate zones. Via species-specific effects on performance and thermal limits (dashed curves, cf. A), additional stressors and species interactions cause shifts in higher-level processes (seasonal activities in response to light or temperature cues, shifts in predator-prey interactions or competition within changing coexistence ranges of interacting species). (D) Shifts in biogeography result during climate warming (modified after Beaugrand, 2009). The polygon delineates the range in space and time, the level of grey denotes abundance. Species display maximum productivity in southern spring, wide seasonal coverage in the centre and a later productivity maximum in the North. The impact of photoperiod increases with latitude (dashed arrow). During warming, the southern temperature and time window contracts while the northern one dilates (directions and shifts indicated by arrows). Control by water column characteristics or photoperiod may overrule temperature control in some organisms (e.g. diatoms), causing contraction of spatial distribution in the north.]

For animals breathing in water (invertebrates and fish exchange respiratory gases with water rather than air; FAQ 6.II), the dimensions of the thermal niche (Figure 6-7A) have been explained by the concept of oxygen and capacity limited thermal tolerance (OCLTT, Pörtner *et al.*, 2010) which integrates findings from ecosystem to molecular levels and explains thermal specialization and associated limitation. For other organisms the respective knowledge explaining thermal reaction norms is not available. Thermal specialization of animals results from economizing energy use, limiting the functional capacity of tissues. Beyond upper and lower thermal thresholds (T_p, Figure 6-7A) tolerance becomes time-limited. At large body size, O_2 supply limitations are exacerbated in the warmth, causing the organism to reach long-term heat limits at lower temperatures. The widths and positions of acute thermal windows on the temperature scale are changing dynamically over time, during short-term or seasonal acclimatization of the individual over days and weeks, during the life cycle of a species and with increasing body size (Figure 6-7A,B) as well as during long-term evolutionary adaptation, across generations, to a climate regime or local conditions (Pörtner, 2006; Pörtner *et al.*, 2008; Eliason *et al.*, 2011). Both acclimatization and adaptation involve adjustments in biochemical characters (membranes, enzymes), and their functional properties, however, the capacity to shift thermal boundaries (Figure 6-7A) is limited to within the thermal niche (Pörtner *et al.*, 2008, 2012). Such limits are effective in the field (Pörtner and Knust, 2007, Katsikatsou *et al*., 2012) and may contribute to the reduction of

abundances during warming (Pörtner and Knust, 2007), to coral losses (Donner *et al.*, 2005), to shifts in the seasonal timing of (zooplankton) biomass formation (Mackas *et al.*, 1998; Goldblatt *et al.*, 1999; Schlüter *et al.*, 2010) or to the reduction of animal body sizes in warming aquatic communities (Daufresne *et al.*, 2009; see examples in 6.3.2) and projected in the 21st century under climate change (Cheung *et al.*, 2012; 6.5). Modelling and paleo-studies have adopted the OCLTT concept to project climate effects (6.5) and explain climate-induced mass extinction events and evolutionary patterns in earth history (Pörtner *et al.*, 2005; Knoll *et al.*, 2007; Knoll and Fischer, 2011).

At community and ecosystem levels, differences in thermal sensitivities and shifts in the relative performance of animal species may underlie their changing competitive or trophic interactions and foodweb structure (Pörtner and Farrell, 2008; Figure 6-7 C), also via shifts in reproductive success, larval output, early juvenile survival and thus recruitment. Knowledge of such high-level functions shaping thermal reaction norms in other organism domains would be essential for a comprehensive view of shifting biogeographies, species interactions, abundances as well as community assemblages and foodwebs in space and time (Beaugrand *et al.*, 2003; Parmesan and Matthews, 2005). Mechanism-based insights link physiological impacts with changing species interactions (e.g. Pörtner, 2010, 2012; Harley, 2011), underpinning scenarios of community level responses to temperature change (Urban *et al.*, 2012), with respect to niche breadth, ecosystem mixing and the resulting extinction threats (6.3), informing modelling (6.5) as well as having implications for conservation and ocean management (6.3., 6.4).

[INSERT FIGURE 6-8 HERE
Figure 6-8: Ranges of temperatures and O_2 concentrations covered by various domains and groups of free living marine organisms (bacteria to animals, domains and groups modified after Woese *et al.*,1990) in various habitats (Storch *et al.*, subm). High organizational complexity enables an increase in body size, associated with decreasing tolerances to hypoxia and heat. In the domain Bacteria, the group Thermotogales comprises obligate anaerobes, displays less complex structures such as a single layer lipid membrane and is most tolerant to high temperatures. Highest temperatures of growth were found at 122°C in hydrothermal vent species under elevated hydrostatic pressure in laboratory experiments. Dashed white arrows denote wide O_2 tolerances in unicellular archeae, bacteria and protists, as compared to animals and plants (multicellular eukarya). Anoxic habitats are conquered by small multicellular and unicellular Eukarya, supported by less complex mitosomes or hydrogenosomes used in energy metabolism. Species richness of animals (upper right) increases with rising O_2 levels reflecting better hypoxia tolerance in small compared to large individuals and their taxa (6.3.3).]

6.2.2.2. Principles of CO_2 Effects in Ocean Acidification

Rising oceanic CO_2 concentrations causing ocean acidification (OA) will have multi-faceted effects on biota. By analogy with thermal stress phenomena, effects mediated by elevated CO_2 levels also range from molecular to systemic, including the neuronal level in animals. OA effects interact with those of other key drivers like temperature and hypoxia (Pörtner, 2010, 2012; Boyd, 2011; Gruber, 2011) and translate from organism into ecosystem level impacts. Meta-analyses of the biological effects of OA indicate that the rate of net calcification (i.e. calcification minus OA-mediated dissolution) is most responsive (Hendriks *et al.*, 2010), however, such meta-analyses cannot resolve for the diversity of species-specific responses, or diverse vulnerabilities of different processes or life stages (Hendriks and Duarte, 2010; Hendriks *et al.*, 2010; Kroeker *et al.*, 2010, 2013).

In marine organisms the diffusive uptake of CO_2 leads to elevated CO_2 partial pressures in all compartments (FAQ). CO_2 causes a (respiratory) acidosis in cells and body fluids which can affect various functions. The weak acid distribution characteristics of CO_2 (Pörtner, 2008, 2012) require a high capacity of ion and acid-base regulation (i.e. of the membrane transporters involved) to balance acidification and readjust setpoints in pH through net base accumulation (e.g. Heisler, 1986; Pörtner *et al.*, 2000; Claiborne *et al.*, 2002; Taylor *et al.*, 2011) (Figure 6-10A). In photolithoautotrophic microbes, accumulating CO_2 or bicarbonate may serve as substrates for metabolism, supporting primary production. The formation of carbonate from bicarbonate is essential in calcification, the formation of calcified structures built by the deposition of solid $CaCO_3$ and used across biota for defence and structural support. Calcification usually occurs in separate body compartments, where even in coccolithophores and corals, pH and thus, the concentration of CO_3^{2-} and Ω of $CaCO_3$ (aragonite, calcite, Mg calcite, 6.1.1) are maintained higher than in other body fluids or ambient water (Trotter *et al.*, 2011; Taylor *et al.*, 2011; McCullough *et al.*, 2012a,

Venn *et al*., 2013). CO_2 impedes the formation of carbonate at calcification sites such that calcification rate decreases or the effect is compensated for by ion transport, incurring elevated energetic costs. In addition, external carbonate shells rely on ambient seawater being supersaturated with regards to carbonates. Otherwise, shells would be dissolved unless protected from direct contact with sea water by organic coating (periostracum) as in molluscs or brachiopods. Falling calcite/aragonite saturation levelsΩ to below unity in the water, as evident in OMZs, favor the dissolution of carbonate shells (FAQ). Table 6-5 summarizes effects of OA in various organism taxa observed in laboratory studies, field experiments (mesocosms) and natural analogues which include submarine CO_2 venting areas in the vicinity of: Ischia, Italy (Hall-Spencer *et al*., 2008), Papua New Guinea (Fabricius *et al*., 2011) or Puerto Morelos, Mexico (Crook *et al*., 2012). With *medium confidence* some species will be tolerant to OA, however, the capacity of sensitive species to acclimatize or adapt remains largely unidentified.

[INSERT TABLE 6-5 HERE

Table 6-5: Assessment of tolerances to ocean acidification in marine taxa, considering the number of laboratory and field studies, and of parameters and species studied in the pCO_2 range from <650 to >10 000 µatm. (Parameters include growth, survival, calcification, metabolic rate, immune response, development, abundance, behaviour and others). Not all life stages, not all parameters and not the entire range of CO_2 concentrations were studied in all species. *Confidence* is based on the number of studies, the number of species studied and the agreement of results within one group. +: denotes that possibly more species or strains (genetically distinct populations of the same species) were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: most species were negatively affected; tolerant: most species were not affected. RCP 6.0: representative concentration pathway with projected atmospheric pCO_2 = 670 µatm, RCP 8.5: pCO_2 = 936 µatm in 2100 (Meinshausen *et al.*, 2011). *Confidence* is limited by the short to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary timescales, across generations (see separate reference list). For an assessment of variability between species from the same phylum see Figure 6-10.]

6.2.2.3. Principles of Hypoxia Effects

The term hypoxia refers to a phenomenon, where ambient PO_2 falls below air saturation and constrains life (6.1.1). Hypoxia affects organisms relying on aerobic metabolism; tolerance thresholds determined as the critical O_2 tension (P_c) or concentration (O_2crit) vary across domains (Figure 6-8) and are high for larger organism. For animals, the P_c is traditionally defined at rest, as the O_2 partial pressure, below which energy turnover falls below regulated rates. At the P_c, a progressive transition from aerobic to anaerobic energy production begins (Pörtner and Grieshaber, 1993). In animals, the P_c is determined by the capacity of ventilatory and circulatory systems in relation to O_2 demand, developmental status, and body size. In active animals with a high O_2 demand or at the extremes of their thermal windows functional constraints set in early, under mildly hypoxic conditions. Most animals can only transiently sustain anaerobic metabolism, even if they are energy efficient and sustain long-term tolerance (Grieshaber *et al.*, 1994). Such time-limited tolerance is highest in large individuals, with a higher capacity of anaerobic metabolism than, for example in larvae, where such tolerance is low (Gray *et al.*, 2002; Jessen *et al*., 2009).

6.2.2.4. Principal Effects on Animals Breathing in Air: Marine Reptiles, Mammals, and Birds

Marine reptiles (sea turtles, marine snakes, crocodiles), mammals and seabirds breathe in air but live mostly in water. Therefore, ocean acidification and hypoxia would have minimal direct influences. There is evidence for increased sound propagation in a CO_2 enriched ocean but no evidence yet for any effect on biota (Ilyina et al., 2010). Hypoxic habitat compression for fishes may enhance the foraging opportunities for their air breathing predators (Hazen *et al*., 2009). Warming waters influence the ectothermic turtles, e.g. through range expansion (McMahon and Hays, 2006) and less so the homeothermic birds and mammals. Large body sizes enable some of these air breathers to travel across the widest aquatic temperature ranges possible and support some of the largest migration ranges on earth. Constraints on thermal tolerance are imposed by various degrees of insulation of the body core in mammals and birds which contributes to constrain their distribution to warmer (poor insulation) or colder waters (high insulation). Their larger independence from physical and chemical drivers in the oceans would make many of these air breathers more resistant to the direct influences of climatic change than fishes or invertebrates but would still expose them to

effects mediated via changes in habitat structure or the food web, related to changes in the availability of prey or other, including alternative food items (6.2.5., 6.3). If habitat structures offering retreat or ambush (e.g. sea ice for polar bears or walrusses) become less available, this will enhance the energetic costs of life. If food items are only found in thermally restricted areas or move to large depths, mammals and birds may be constrained to certain distribution ranges or exploitation of their physiological dive limits (McIntyre *et al*., 2011). Compared to oceanic migrators shifts in prey distributions and resultant oceanic habitat may have effects on the physiological costs of finding prey for foragers that are tied to land between trips (Hazen *et al*., 2012; Péron *et al*., 2012).

6.2.2.5. Principal Effects of Changes in Light, Nutrient, and Food Availability

In addition to temperature and CO_2, availability of light and nutrients to photoautotrophs may be altered directly or indirectly with a changing climate, partly through density-related stratification (Figure 6-9), the circulation regime at different spatial scales and the physical displacement of organisms. The supplies of major plant nutrients (macro-nutrients) such as nitrate, and of micronutrients such as iron (Pitchford and Brindley (1999) vary both seasonally (Boyd, 2002), regionally (Moore *et al.*, 2002) and with the current regime and may involve simultaneous limitation (co-limitation) by more than one resource (Saito *et al.*, 2008). Nutrients provide the elemental building blocks for macromolecules needed for cellular physiology. The net result of climatic change affecting all of these processes may be changes in primary productivity due to changing rates of photosynthesis and other physiological processes, as well as changes in community composition. For heterotrophs, from bacteria to fish, mammals and birds, the uptake of organic material as food, ultimately provided by primary production, is central not only to productivity but also for fueling energy consuming functions including the resistance of organisms to environmental change and pathogens (6.2.5., 6.3.6). Any direct influence of climate on the abundance and quality of feed organisms will thus translate to indirect effects on the productivity and well-being of foraging animals (Figure 6-7A,C).

6.2.2.6. Conclusions

Integrating findings across levels of biological organization, molecule to ecosystem, support a comprehensive cause and effect understanding of climate change effects on marine biota (*high confidence*). Some of the respective understanding is emerging but is fragmentary for many organism groups. Experimental observations therefore are largely empirical and cannot easily be scaled up to projecting species-specific responses. The principles of thermal reaction norms are not yet widely applied across organism domains (*medium evidence, limited agreement*) but the recent emergence of converging approaches from empirical, modeling and ecological studies enhances *confidence* to *high* as to their usefulness for developing coherent approaches in all organisms.

6.2.3. Microbes – Link to Biogeochemical Processes

The phylogenetic and metabolic diversity of the microbial world (6.2.1) sustains many unique cellular and key ecosystem processes such as CO_2 fixation and O_2 production, the conversion of nitrogen into ammonia (N_2 fixation), and the use of nitrate, sulphate, CO_2 and metals (Fe and Mn) as terminal electron acceptors in metabolism when O_2 is absent. Microorganisms also catalyze the horizontal transfer of genetic information between unrelated individuals, thereby enhancing biodiversity (McDaniel *et al*., 2010). Microorganisms also catalyze the horizontal transfer of genetic information between unrelated individuals, thereby enhancing biodiversity. The development of a better understanding of climate-induced alterations in the functioning of microorganisms builds on laboratory, mesocosm, and in situ studies as well as modeling. Together, these data will eventually inform us of what regions and which taxonomic groups are more susceptible to climate change and consequently where in the ocean to look for the biological imprint of a changing ocean (Boyd *et al.*, 2011).

6.2.3.1. Temperature – Related Processes

A warming ocean may initially enhance the metabolic rates of microbes (Banse, 1991) and stimulate their overall growth as in phytoplankton (Bissinger *et al*., 2008) but eventually challenge their thermal tolerance –as described by organismal performance curves (i.e. fitness versus environment) for different groups (Chevin *et al.*, 2010), leading to competitive advantages and species replacements. Ocean surveys of phytoplankton size structure revealed increasing fractions of small cells in warmer waters (Morán *et al.*, 2010). However, further experimental and field observations (Giovannoni and Vergin, 2012) are required to validate model projections (Taucher and Oschlies, 2011) of differential responses to warming by different microorganisms.

A coastal experimental microcosm study reports that resident heterotrophic bacteria are more responsive to warming than a laboratory-reared phytoplankter and hence this study illustrates the potential biogeochemical implications of a non-linear ecological response to warming, i.e. greater stimulation of bacterial rate processes relative to that for phytoplankton, within upper ocean foodwebs (Wohlers-Zöllner *et al*., 2011). Consistent with the finding of a warming induced shift to heterotrophy along a high to low latitude survey transect in both the North and South Atlantic (Hoppe *et al*., 2002), it has been hypothesized that heterotrophy might then play a bigger role in warmer oceans and hence microbially-mediated carbon flow to the atmosphere (i.e. CO_2 efflux,or outgassing) might increase (Sarmento *et al*., 2010). The underlying principles and wider applicability of these findings remain to be established (Kirchman *et al*., 2009) in further comparative studies (*limited evidence, low agreement*).

6.2.3.2. Irradiance

The range and mean level of underwater irradiances (light climate) encountered by phytoplankton will be altered by a changing climate (Doney, 2006), due to changing surface mixed layer depth, cloudiness and/or to alteration of sea-ice areal extent and thickness. The physiological response of phytoplankton to higher or lower irradiances caused by the predicted shallowing of the mixed-layer depth (6.1.1) and loss of ice cover, involves photophysiological acclimation via changes in cellular chlorophyll which is however constrained by unidentified limits to its plasticity (Falkowski and Raven, 1997). A longer growing season, due to more sea-ice free days, may have increased productivity (based on a time-series of satellite ocean color and a primary productivity algorithm) in Arctic waters (Arrigo and van Dijken, 2011). This study showed that the average annual NPP increased by an average of 8,1 Tg C yr^{-1} between 1998 and 2009, strongest between 2003 and 2007. In addition, massive under-ice blooms have been observed favored by light penetrating surface melt ponds and first-year ice (Arrigo *et al*., 2012). Little is known about expected shifts from sea-ice algae to free-drifting phytoplankton with a decrease in sea-ice cover and increased irradiance in polar waters in the coming decades. As some krill predominantly feed on sea ice algae, it is unclear (*low confidence*) whether they will be able to adapt to feeding on free drifting phytoplankton (Smetacek and Nichol, 2005).

6.2.3.3. Stratification – Nutrient and Irradiance Controls on Primary Production

A stronger vertical density gradient will reduce the communication between the sunlit upper ocean where photosynthesis takes place and the underlying nutrient-rich waters (Doney, 2006; Figure 6-9). Lower chlorophyll concentrations at warmer sea surface temperature in nutrient-poor low latitude waters, based on ocean color data, have in fact been interpreted as an effect of increased stratification on phytoplankton stocks (Boyce *et al.*, 2010). In contrast, higher chlorophyll concentrations at warmer sea surface temperature were found at high latitudes (Boyce *et al.*, 2010). It has thus been suggested based on *limited evidence* and *low agreement* due to methodological uncertainties (6.1.3) that expanding, permanently stratified, low chlorophyll, tropical regions (WGI Ch. 3), will result in declining phytoplankton stocks in the warming oligotrophic waters of the N and S Pacific and N and S Atlantic (Polovina *et al.*, 2008; Signorini and McClain, 2012; 6.3.1). Furthermore, increased frequency of, or a transition to, permanent El Niño favorable conditions in a warmer future world (Wara *et al.*, 2005) and further expansion of subtropical ocean gyres (Polovina *et al.*, 2008), may lead to lower global ocean NPP.

[INSERT FIGURE 6-9 HERE
Figure 6-9: Projected alteration of oceanic properties and atmospheric events due to a changing climate. Properties will be altered across the water column, from the mid-water stratum to the sunlit surface layer, and will influence the fitness of the residence biota. Changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean ecosystems (courtesy of Boyd and Law, 2011).]

However, projections of a global decrease in phytoplankton biomass have been refuted (McQuatters-Gollop *et al*., 2011; Mackas, 2011; Rykaczewski and Dunne, 2011). Time series with shorter than 20 years of observations do not resolve impacts of bidecadal variation such as the Pacific Decadal Oscillation or the lunar nodal cycle (e.g. Watanabe *et al*., 2008; Henson *et al*., 2010). Analysis of continental shelf ecosystems, including field data in the most productive upwelling areas covering the last 20 years (e.g. Chavez *et al*., 2011), revealed a large variety of trends at scales of several decades but a general increase of carbon fixation by phytoplankton on most shelves (Sherman and Hempel, 2009; Chavez *et al*., 2011; Bode *et al*., 2011), possibly caused by both climate change and by anthropogenic eutrophication. As satellite trends do not encompass the variability in subsurface chlorophyll (6.1.3) the putative enhancement of primary productivity at the nutricline (Whitney, 2011) remains undetected. Recent field studies point to a growing fraction of primary production derived from atmospheric N in large ocean basins (e.g. Mouriño-Carballido *et al*., 2011). In the presence of sufficient phosphate, fixation of atmospheric N may gain importance in warmer and stratified tropical and subtropical oceans (e.g. Sohm *et al*., 2011).

6.2.3.4. Ocean Acidification – Effects of Anthropogenic CO_2 Concentrations and Water pH

The physiological effects of ocean acidification (OA) appear to be species- and even population-specific. Elevated surface ocean CO_2 partial pressures (pCO_2) may lead to fertilization of phytoplankton but effects are species- or taxon-specific possibly depending on how they acquire carbon (i.e., the presence and in particular the type, capacity and energetic costs of carbon-concentrating mechanisms (CCM's, Giordano *et al.*, 2005; Kranz *et al.*, 2011; 6.2.2). Diatoms are considered to be relatively insensitive to elevated CO_2 with regard to growth and fixation rates (Rost *et al.*, 2003; Trimborn *et al.*, 2008), yet there are indications for CO_2-induced stimulation of primary production rates (Tortell *et al.*, 2008b). For dinoflagellates, relatively little is known with regard to their sensitivity to elevated CO_2 (Hansen *et al.*, 2007) although in one species carbon fixation rates were enhanced at 750 µatm CO_2 while growth remained unaffected (Fu *et al.*, 2008).

Changes in calcification under OA are species-specific. Overall, there is *medium evidence and low agreement* that CO_2 induced OA will result in exoskeletons that are insufficiently calcified for sustained structural support and protection. In coccolithophores, the response is highly variable, uncertainty is high as the function(s) of calcification are not known and consequences of lowered calcification are difficult to be estimated (e.g.Trimborn *et al*., 2007; Rost *et al*., 2008). Reductions, increases and unchanged shell architecture or calcification rate have been documented for RCP 8.5 CO_2 conditions projected around 2100 in different coccolithophore species (Riebesell *et al.*, 2000; Zondervan *et al.*, 2001; Langer *et al.*, 2006; Iglesias-Rodriguez *et al.*, 2008) with species-specificity (Langer *et al.*, 2006) and strain-specificity for calcification in *Emiliana huxleyi* (Langer *et al.*, 2009; Hoppe et al., 2011; Langer *et al.*, 2011) (see Table 6-6 for details). Low light (Zondervan *et al.*, 2002) or nitrogen limitation (Sciandra *et al.*, 2003) are suggested to limit the beneficial effect of OA on photosynthesis and to have a strong negative effect on calcification (Sciandra *et al.*, 2003; Rokitta and Rost, 2012). Nutrients and light cause functional adjustments through gene expression (Dyhrman *et al*., 2006; Richier *et al*., 2009).

[INSERT TABLE 6-6 HERE
Table 6-6: Selected ocean acidification effects on microbes and associated processes.]

Likewise, laboratory studies on planktonic N_2 fixing cyanobacteria (termed diazotrophs) indicate that some of these organisms respond to changing CO_2. In particular, strains (genetically distinct populations of the same species) of offshore cyanobacteria belonging to the genera *Trichodesmium* and *Crocosphaera* increased rates of carbon and N_2 fixation under elevated CO_2 (Lomas *et al*., 2012). However, the resulting responses in N_2 fixation have varied widely (Barcelos e Ramos *et al.*, 2007; Hutchins *et al.*, 2007; Levitan *et al*., 2007; Kranz *et al.*, 2010; Lomas *et al*., 2012) and not all marine N_2 fixing cyanobacteria increase rates of N_2 fixation under elevated pCO_2. Laboratory studies using the

bloom-forming cyanobacteria *Nodularia* (an organism largely found in stratified, eutrophic waters) revealed decreased growth and N_2 fixation under elevated CO_2 conditions (Czerny *et al.*, 2009). To date, the mechanisms underlying these observed physiological responses, especially those in open ocean nitrogen fixers, remain unknown. Cyanobacteria may reallocate energy from their costly CCMs toward N_2 fixation and acquisition of growth limiting nutrients (Kranz *et al.*, 2010; Levitan *et al*., 2010b). However, evidence for such diversion of energy from CCMs toward N_2 fixation is lacking. *Confidence* is thus *low* based on *limited in situ evidence* and *medium agreement* that there is an increase in nitrogen fixation with progressive ocean acidification.

6.2.3.5. Bacterial Life in Hypoxia and Anoxia – Oxygen Minimum Zones (OMZ)

Heterotrophic energy yield with O_2 is largest and is generally preferred over the use of alternate electron acceptors. It has only recently been shown that some bacteria can still grow aerobically and efficiently at even nanomolar O_2 concentrations (Stolper *et al.*, 2010). This has important implications for the formation of 'oxygen minimum (or even free) zones' (OMZs). R*obust evidence* indicates that bacteria both create and sustain OMZs by their diversity and plasticity of metabolism. Wherever the consumption of organic matter supporting bacterial metabolism exceeds the rate of O_2 re-supply, an OMZ will be formed, also characterized by elevated pCO_2 and enhanced acidification. With *high confidence*, OMZs are therefore a consequence of high organic loading or restricted water movement, or both (6.1.1; WGI Box 6.5, Figure 1). Most marine sediments also have OMZs due to limited penetration and exchange of dissolved O_2 with the bottom water. OMZs have also been detected in coastal waters downstream of regions of high inorganic nutrient or organic matter loading. Natural variation in thermocline depth can counter effects of OMZ expansion in the open sea (6.1.1., 6.3.3) by limiting oxidative demand in deepened, warmer, low O_2 thermocline waters (Deutsch *et al.*, 2011). Therefore, OMZ expansion may not be manifested as a monotonic change, but rather be complicated by decadal climate events.

6.2.3.6. Conclusions

While various physiological processes are known to respond to changes in irradiance, nutrient supply, temperature, CO_2 or hypoxia in microbes, the knowledge base on how these processes may be altered does not (yet) include a conceptual foundation suitable to support an integrated understanding of climate impacts on individual species and in turn on communities. The data available are patchy and the reported data trends are often in different directions, partly due to the application of different experimental protocols and/or the over-reliance on species or strains of microbes that are readily culturable and hence have been used for decades in laboratory research. *High confidence* is thus presently limited to the attribution of specific physiological responses of microorganism species, such as primary production, N_2 fixation, or calcification, to environmental drivers associated with climate change.

6.2.4. Macrophytes - Effects of Temperature and Ocean Acidification

Macrophytes (seaweeds and seagrasses) in the transition zone to coastal waters (WGII Ch. 5) cover only 0.6 % of the world's marine areas (Smith, 1981) but their production amounts to almost 10 % of total oceanic production (Charpy-Roubaud and Sournia, 1990). Their thermal growth-response curves (Figure 6-7) show a clear link between production and the local temperature regime. Temperate species with wide windows of thermal tolerance (Figure 6-2) acclimatize by shifting these windows following the seasonal temperature change (Kübler and Davison, 1995). Antarctic or tropical macroalgae are exposed to permanently low or high temperatures and have consequently specialized on limited temperature variability, paralleled by a low acclimatization potential (Pakker *et al.*, 1995; Eggert and Wiencke, 2000; Eggert *et al.*, 2006; Gómez *et al.*, 2011). In the tropics, observations indicate that seagrasses tolerate higher temperatures than seaweeds (Campbell *et al*., 2006). As in other organisms, the molecular basis of acclimatization and its limitation in relation to the climate regime require further study.

Primary production, shoot density, reproductive output and/or below-ground biomass of seagrasses generally respond positively to elevated pCO_2, indicating CO_2 limitation of their productivity. Such effects were identified in the laboratory and the field in the range above 720 to 1800 µatm (*high confidence*, e.g. Palacios and Zimmerman,

2007; Hall-Spencer *et al.*, 2008; Andersson *et al.*, 2011). Similarly, most non-calcifying seaweeds exhibit significantly increased production, growth and recruitment at CO_2 levels above 700 to 900 µatm (Kroeker *et al.*, 2010). In some macroalgae, such stimulation only occurs in combination with elevated temperature (Connell and Russell, 2010) or not at all (Porzio *et al.*, 2011). In experiments, calcifying algae show complex and species-specific responses of photosynthesis and/or carbon production to elevated CO_2, but calcification is highly impacted beyond species-specific thresholds of pCO_2 (*medium confidence*, Anthony *et al.*, 2008; Ries *et al.*, 2009, Ragazzola *et al.*, 2012). Calcification by temperate coralline red and calcareous green algae increased with rising CO_2 levels up to 900 µatm and only decreased at the highest concentration applied (2850 µatm) but did not fall below control rates (Ries *et al.*, 2009). During 3 months of CO_2 exposure, growth of cold water *Lithothamnion glaciale* decreased progressively with rising CO_2 levels. Structural integrity was weakened beyond 590 µatm (Ragazzola *et al*., 2012).

In conclusion, *confidence* is *high* that macrophytes specialize on limited temperature ranges, are sensitive to temperature extremes and that CO_2 stimulates primary production of some macroalgae and seagrass species. With *medium confidence*, calcifying species do not benefit and will be less competitive in a high CO_2 ocean.

6.2.5. Animal Performance and Sensitivities – Fitness and Interactions in Various Climate Zones

Climate change has the potential to affect all animal phyla, from ectotherms (like turtles, with a body temperature that fluctuates with ambient temperature) to endotherms (like mammals and seabirds which generate metabolic heat to sustain a constantly elevated body temperature) through effects on individual organisms, populations and communities or on species interactions and the food web. Existing knowledge of the principles of effect increases confidence in projections of future change (6.2.2).

6.2.5.1. Temperature-Dependent Biogeography and Species Interactions

The distribution, abundance and population dynamics of marine fishes and invertebrates correlate with climate change and climate variability monitored by hydro-climatic indices such as AMO or NAO (6.1.2). Ecosystem shifts attributed to climate change (Hoegh-Guldberg and Bruno, 2010) have mostly been related to temperature. Although temperature means are still most commonly used in marine attribution studies, temperature extremes rather than means are most often mediators of effects (Easterling *et al.*, 2000; Grebmeier *et al.*, 2006; Pörtner and Knust, 2007; Wethey *et al.*, 2011; Wernberg *et al*., 2013; Figure 6-7; 6.2.2). During heat exposure near biogeographical or equivalent limits (including the high intertidal or warming surface waters), reductions in growth, activity and abundance of fish and invertebrate populations set in with even small (<0.5°C) shifts in ambient temperature extremes (Takasuka and Aoki, 2006; Pörtner and Knust, 2007; Farrell, 2009; Nilsson *et al.*, 2009; Neuheimer *et al.*, 2011). Local extinction events follow due to mortality or behavioral avoidance of unfavorable thermal environments (Breau *et al.*, 2011). Shifted biogeographies follow clines from high to low temperature, along latitudes, an equivalent lateral gradient (Perry *et al*., 2005) or even a vertical gradient to deeper waters (Dulvy *et al*., 2008; Graham and Harrod, 2009, Figure 6-7).

In marine animals, the widths of thermal windows roughly match ambient temperature variability (Figure 6-2) according to climate regime and seasonality (Sunday *et al*., 2012). A comparison of fishes across latitudes suggests that high latitude polar species have narrow windows (stenotherms), species at temperate mid latitudes have the widest windows (eurytherms) and ranges are intermediate at tropical latitudes (Pörtner and Peck, 2010). Higher variability in atmospheric and ocean temperatures characterizes the Northern versus the Southern hemisphere (Jones *et al*., 1999, Figure 6-2), resulting in wider temperature ranges in Northern invertebrates and fishes and making them less vulnerable to warming than Southern ones, especially at sub-polar latitudes.

Wide thermal windows are often associated with higher energetic costs, reflected in high resting metabolic rates, as seen in sub-Arctic (Pörtner, 2006), small or highly mobile species (Pörtner, 2002b). Conversely, polar species with narrow thermal windows have low levels of energy demand. Variability in thermal windows between coexisting species is even found among Antarctic stenotherms (Peck *et al.*, 2009) and has implications for their relative climate sensitivity, their potential interactions (Milazzo *et al*., 2013) and community composition. Such principles (6.2.2)

may underlie "regime shifts" between coexisting species (Pörtner, 2012; Table 6-7). Critical mismatches between predator and prey organisms may cause abundance losses or local extinctions (Figure 6-7D; Beaugrand, 2009).

In the lifecycle of species, early life stages or adult spawners may be more sensitive to warming because of their narrower thermal windows, e.g..on the cold side for winter spawning Atlantic cod (Table 6-7). For bigeye, bluefin or skipjack tuna, effects during early life stages are less clear, their thermal window is also narrow, but at high temperatures. If adults spawning at high temperature need to prevent overheating, a compensatory shift in location to cooler (deeper) waters may occur (Lehodey *et al*., 2011). Indirect effects of warming, such as the changing composition and biomass of food, depend on ocean stratification and productivity, or expanding OMZs (6.3.2.-3).

[INSERT TABLE 6-7 HERE
Table 6-7: Examples illustrating species vulnerabilities and underlying mechanisms to changing temperature, hypoxia, ocean acidification (OA).]

Local adaptation may be strong in organisms living in heterogeneous environments like the intertidal (Kelly *et al*., 2012), causing functional differentiation. Functional and genetic differentiation into populations supports the wide biogeographical ranges of species like Atlantic cod and its ongoing invasion of Arctic waters (Pörtner *et al*., 2008). Acclimatization capacity is small in high polar, e.g. Antarctic species (Peck *et al*., 2010). In general, species at their warm or cold distribution limits have exploited their acclimatization capacity. Tropical reef fishes undergo rapid warm acclimation across generations (Donelson *et al.*, 2012); again, mechanisms and capacities are poorly known.

6.2.5.2. Hypoxia Effects

Animal life in low oxygen conditions (hypoxia) requires adaptations leading to a reduction in O_2 and energy demand, and the improved ability to efficiently extract O_2 from the water and transport it to tissues. This lowers the minimum oxygen content in the water that is needed to sustain life. This critical O_2 threshold (P_c, 6.2.2) varies with life stage, body size, temperature, consumed food, O_2 demand and is influenced by other environmental stressors (Pörtner, 2002b; Ekau *et al.*, 2010; Seibel, 2011). On average, large, more active animals have high O_2 demands, for example fishes, crustaceans and muscular squids, associated with high P_c thresholds and are, therefore, sensitive to permanent hypoxia. However, even in high activity animal groups some specialists such as Humboldt squid or bigeye tuna have adapted to live temporarily in hypoxic environments (Childress and Seibel, 1998; Richards *et al.*, 2009; Seibel, 2011). Time-limited tolerance is sustained by the depression of energy demand, for example during periods of metabolic arrest (e.g. developmental arrest or diapause of copepods; Auel *et al.*, 2005).

Hypoxia reduces tolerance to high temperature extremes, because oxygen demand and P_c rise with increasing temperature, reflecting increasing difficulty for animals to get enough oxygen and fuel their activities. This may occur fastest in warm oceans, where metabolic rates are higher and animals live closer to upper thermal limits (Pörtner, 2010). Conversely, high oxygen availability alleviates thermal stress (Mark *et al.*, 2002; Pörtner *et al.*, 2006) and acclimation to hypoxia increases thermal tolerance (Burleson and Silva, 2011), for example by enhancing blood pigment content or reducing energy demand.

Permanent life in the OMZ relies on energy demand being covered exclusively by aerobic metabolism. This is supported by cold temperature which causes energy demand to be low and, thereby, supports P_c thresholds to remain below ambient O_2 levels. Finally, low O_2 levels support a high abundance of meiofauna (very small fauna, <1mm), because their O_2 extraction from the water is facilitated by the combination of reduced energy demand and small body size (Yang *et al.*, 1992; Vetter *et al.*, 1994; Childress and Seibel, 1998; Pörtner, 2002b; Levin *et al.*, 2009). Moreover, food is abundant and predation by larger organisms reduced (Levin, 2003). Under extreme hypoxia (suboxia) only specialists can survive, resulting in a loss of biodiversity (Vaquer-Sunyer and Duarte, 2008). Once approaching anoxia, the centres of pelagic OMZs and benthic dead zones exclude animal life (Levin, 2003). Calcifiers, due to the lowering of metabolic rates at elevated pCO_2 are marginalized in OMZs (Levin, 2003).

6.2.5.3. Effects of CO_2-induced Ocean Acidification

The responses of invertebrates and fish to CO_2 imply sometimes positive but mostly negative effects on fitness with variable sensitivities between species and life stages within and across phyla. Present findings indicate a key role for extracellular pH in modulating the responses of various processes to elevated CO_2 (Figure 6-10A). The effects of a lowered pH (acidosis) on processes in organs like muscle or liver may explain when whole organism energy demand falls (Pörtner *et al*., 1998; Michaelidis *et al*., 2005; Langenbuch *et al.*, 2006; Pörtner, 2008; Liu and He, 2012), probably paralleled by reduced rates of ion exchange, protein synthesis, growth and feeding (Table 6-7).

The acidosis can be fully or partially compensated for and animal performance maintained by the stimulation of acid-base regulation and associated ion exchange (Figure 6-10A). Compensation, however, may cause increased energy demand and metabolic rates. Costs may increase for ion exchange or for calcification or growth. In fact, at mildly elevated CO_2-levels in rock oysters (Parker *et al.*, 2011) or in krill (Saba *et al*., 2012) energy turnover and ingestion rate (krill) increased, indicating significant capacity to resist the CO_2-induced depression of performance. Stimulation of growth induced by CO_2 has also been reported (cf. Gooding *et al*., 2009; Munday *et al.*, 2009b; Dupont *et al*., 2010) and might involve not only sufficient compensation but also enhanced energy efficiency under CO_2. Full exploitation of this ability depends on the availability and quality of food which in turn may support fitness and stress resistance (Gooding *et al.*, 2009, Melzner *et al*., 2011). A decrease in food quality of a diatom led to slower growth and reproduction of the copepod *Acartia tonsa* (Rossoll *et al*., 2012).

Sensitivity to CO_2 then relates to the capacity of acid-base regulation (Figure 6-10A). Such capacity can be upregulated during acclimatization, indicated by enhanced gene expression of ion exchange proteins as seen in echinoderm larvae (O'Donnell *et al*., 2010; Martin *et al.*, 2011), or in fishes (Deigweiher *et al.*, 2008; Tseng *et al*., 2013). In general, such capacity is higher in more active marine animals with high metabolic energy turnover, among fishes, cephalopods and also copepods, coastal crabs when compared to sessile, more inactive species (Table 6-7), Pörtner *et al*., 2005, 2011; Ishimatsu *et al.*, 2008; Melzner *et al.*, 2009; Ishimatsu and Dissanayake, 2010). The capacities of acclimatization and adaptation processes, as well as their limits in shifting tolerances remain to be explored.

[INSERT FIGURE 6-10 HERE
Figure 6-10: Top: Responses of a schematized marine animal (blue line) to ocean acidification (OA). Effects are mediated via diffusive entry of accumulating CO_2 (dark green, black arrows) into body compartments, resulting in a drop in compartmental pH (highlighted in red) and its effects (red dashed arrows) on various processes (light blue) as well as calcium carbonate saturation state (Ω) at calcification sites (after Pörtner, 2008). Variable sensitivity depends on the degree of pH decline and compensation, depending on the capacity of transmembrane ion transport. Bottom: % fraction of studied scleractinian coral, echinoderm, molluscan, crustacean and fish species affected negatively, positively or not at all by various levels of ambient CO_2. Effects considered include those on life stages and processes reflecting physiological performance (O_2 consumption, aerobic scope, behaviours, scope for behaviours, calcification, growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, morphology). As not all life stages, parameters and pCO_2 ranges were covered in all species two assumptions partially compensate for missing data: 1) Negative effects at low pCO_2 will remain negative at high pCO_2. 2) A positive or neutral outcome at both low and high pCO_2 will be the same at intermediate pCO_2. As responses reported for each species vary for each CO_2 range, variable species numbers result (on top of columns). The total number of species studied for a given group is represented as the number above the control column. Horizontal bars above columns represent frequency distributions significantly different from controls (from Wittmann and Pörtner, subm).]

In some cases, species might not be able to compensate despite a rise in whole organism metabolic cost. Possibly, extracellular acidosis persists and/or imbalances in energy budget result; e.g. some tissues like epithelia or calcification compartments may display enhanced costs, exceeding the downregulation of metabolism in others, e.g. muscle or liver. Enhanced calcification can then occur at the expense of somatic growth (Wood *et al.*, 2008; Beniash *et al.*, 2010; Thomsen and Melzner, 2010; Parker *et al.*, 2011). It was recently discovered that elevated CO_2 can cause behavioral disturbances in larval and juvenile coral reef fishes, while growth was reportedly undisturbed or even stimulated (Munday *et al.*, 2009b, 2011b). The behavioral disturbances would make fishes as sensitive as the

other animal phyla (Figure 6-10B; Munday *et al.*, 2010; Ferrari *et al*., 2011; Devine *et al*., 2012; Domenici *et al*., 2012). The neural sensitivity to moderate CO_2 increases seen in tropical reef fishes (Nilsson *et al*., 2012) warrants study of its long-term persistence and in species from other climate zones before general conclusions can be drawn.

Changes in calcification rates seen in experiments on animals vary largely but meta-analyses show a decrease to be the most uniform response (Box CC-OA). Reduced calcification and weakened calcified structures were seen in corals (see below, Box CC-CR), echinoderms, molluscs and, possibly, crustaceans (Kurihara and Shirayama, 2004; Arnold *et al.*, 2009; Comeau *et al.*, 2009; Lischka *et al.*, 2011). Some species enhanced calcification above control rates in the range of pCO_2 from 600 to 900 µatm (Ries *et al.*, 2009). Enhanced calcification in juvenile cuttlefish (cephalopods) and fishes (Gutowska *et al.*, 2008; Checkley Jr *et al.*, 2009; Munday *et al.*, 2011a) yielded stronger cuttlebones or otoliths. The role of enhanced calcification for fitness remains unclear.

Studies analyzing animal sensitivities to OA during their whole life cycle or during critical transition phases (e.g. fertilization, gastrulation, egg hatching, metamorphosis, moulting) are scarce (Table 6-7). In sensitive species from various phyla, early life stages appear most vulnerable. With delayed development, extended predator exposure of larvae may lead to enhanced mortalities. Effects on one life stage may carry over to the next one. Moulting success into the final larval stage was reduced in a crab (Walther *et al.*, 2010). In a sea urchin, negative impact was found to accumulate from larvae to juveniles and during 4 months acclimation from adults to larvae. This latter impact was, however, compensated for during extended acclimation of females for 16 months (Dupont *et al*., 2012), emphasizing the need for long-term acclimation studies to realistic scenarios. In an oyster species, however, enhanced resistance was carried over to offspring when parents were pre-exposed to elevated CO_2 levels (Parker *et al.*, 2012). It remains to be explored whether and to what extent animal species undergo evolutionary adaptation to progressive ocean acidification over generations. While this process is constrained by long generation times, it is facilitated by high phenotypic variability among larvae (Parker *et al*., 2011, 2012; Sunday *et al*., 2011). This may also explain the selective mortality seen in Atlantic cod larvae under elevated CO_2 (Frommel *et al*., 2012).

A meta-analysis of responses to CO_2 showed species- and taxon-specific sensitivity distributions in metazoa (Figure 6-10B), with various processes affected (Table 6-7; Box CC-OA). Echinoderms, the molluscan bivalves and gastropods as well as corals begin to respond negatively at lower CO_2 levels than crustaceans or cephalopods (Figure 6-10B). This sensitivity pattern resembles observations for the Permian mass extinction (Knoll *et al.*, 2007; Knoll and Fischer, 2011). The picture for fishes is less clear as the present findings of high sensitivity are not met by similar observations in the fossil record. Evolutionary adaptation may thus eliminate or minimize reported effects.

In general, effects of ocean warming, acidification and hypoxia may operate through interrelated physiological mechanisms (Pörtner, 2012). Such knowledge helps to reconcile apparently contrasting findings. For example, warming below the thermal optimum stimulates physiological processes beneficial for resistance to OA; compensation of CO_2 induced disturbances of growth and calcification has in fact been observed (Brennand *et al.*, 2010; Findlay *et al.*, 2010; Walther *et al.*, 2011). Warming to above optimum temperatures, however, exacerbates sensitivity to CO_2 and conversely, CO_2 enhances heat sensitivity in crustaceans (Walther *et al.*, 2009; Findlay *et al.*, 2010), coral reef fishes (Munday *et al.*, 2009a) and corals (via CO_2-enhanced bleaching; Anthony *et al.*, 2008; 6.2.2., Figure 6-7), causing a narrowing of the thermal niche (Walther *et al.*, 2009; Figure 6-7; 6.3.5).

The climate zone may thus shape CO_2 sensitivity due to differences in temperature, ocean chemistry and organism physiology. Elevated energy turnover in Northern hemisphere ectotherms (see above) may improve resistance, associated with a higher capacity in acid-base regulation. In contrast, low energy expenditure in Southern, deep sea and high polar, e.g. Antarctic species, may cause enhanced sensitivity (e.g. crustaceans, Pane and Barry, 2007). Reported patterns of acid-base regulation in Antarcic fishes under OA are unusual and their influences on sensitivity unclear (Strobel *et al*., 2012). Polar calcifiers are exposed to higher CO_2 solubility and lower carbonate saturation levels, possibly exacerbating sensitivity (Orr *et al.*, 2005). Tropical species may again be specialized and more sensitive than species from temperate regions (Pörtner *et al.*, 2011). This rough differentiation is complicated by local adaptation from within species genetic variability. At present, it is unclear if evolutionary adaptation to elevated CO_2 levels has occurred in polar waters, OMZs or marine sediments, possibly with reduced reliance on the strength of calcified structures (Clark *et al.*, 2009; Walther *et al.*, 2011; Maas *et al*., 2012).

6.2.5.4. Sensitivities of Warm and Cold Water Reef-building Corals

Tropical corals differ from most other animals by forming an endosymbiosis with dinoflagellates of the genus *Symbiodinium*, which enable their hosts to build and sustain carbonate reefs and their functions (Box CC-CR). *Symbiodinium* provides the host with organic carbon from photosynthesis (Trench, 1979; Pernice *et al*., 2012) and is provided with inorganic nutrients which are in short supply in clear tropical waters (Muscatine and Porter, 1977; Muscatine and D'elia, 1978). Unusual changes in light or salinity and small changes in temperature correlate with 'bleaching', the loss of symbionts and tissue color, possibly caused by Reactive O_2 Species (ROS). Damage to the symbionts involves disturbed excitation processing within the light harvesting centers of photosynthesis (Glynn and D'croz, 1990; Hoegh-Guldberg and Smith, 1989) and ROS release, also affecting CO_2 fixation by Rubisco (Ribulose Bisphosphate carboxylase, Jones *et al*., 1998) and/or photosystem II (PSII) functioning (Warner, 1999). Mass bleaching is correlated with small temperature anomalies (+1-2 °C of the long-term summer maximum, satellite observations), causing mortalities (Goreau and Hayes, 1994; Strong *et al*., 1997, 2011) and an observed average decrease in coral abundance by 1-2 % per year (Carpenter *et al*., 2008; Box CC-CR). It is debated whether corals adapt to warming (Box CC-CR), by considering shifting heat tolerances across coral genera (Hoegh- Guldberg and Salvat, 1995; Loya *et al*., 2001), the exchange of genetic clades of *Symbiodinium* with more tolerant varieties (Baker, 2001, 2004; Jones *et al*., 2008; Ulstrup and Van Oppen, 2003), as well as acclimatization phenomena (Howells *et al*., 2012). It remains unexplored whether such mechanisms can sustain reef formation.

OA causes genera-specific reductions in calcification (Kleypas et al., 1999, Hoegh-Guldberg *et al*., 2011; Kleypas and Langdon, 2006; Langdon and Atkinson, 2005; Leclercq *et al*., 2002). Coral communities around natural CO_2 seeps have lower growth, calcification and biodiversity (Manzello *et al*., 2008; Fabricius *et al*., 2011) and display a shift from net accretion to net erosion, depending on ambient CO_2 levels (Box CC-CR). Nutrient availability to symbionts may sustain calcification. Females may sacrifice calcification more than males due to energetic tradeoffs with reproduction (Holcomb *et al.*, 2010, 2012). Heterotrophic feeding supporting resilience (Edmunds, 2011) shows the energy dependence of coral calcification and acid-base regulation (Figure 6-10).

Temperature extremes acting synergistically with CO_2 reduce calcification and increase sensitivity to bleaching (Anthony *et al*., 2008; 6.3.5). Combined warming and OA following B2 and A1FI AR4 scenarios in mesocosms caused losses of symbionts and corals, and a nocturnal decalcification of the reef community in summer (Dove *et al.*, subm). Wide changes occur in gene expression including ones involved in carbonate deposition and skeleton formation (Kaniewska *et al*., 2012). Mechanisms of temperature and OA impacts clearly require further study.

Studies of the climate sensitivity of cold water corals are scarce. Findings that *Lophelia pertusa* respond strongly to 3°C warming, with a three-fold increase in metabolic rate (Dodds *et al.*, 2007) indicate that these have narrow thermal windows (cf. Pörtner, 2006). Three studies provided proof for resilience of *L. pertusa* to ocean acidification. In short-term ship-board incubations and with pH reductions of between 0.15 and 0.3 units, (Maier *et al.*, 2009) found calcification rates reduced by 30-56 %, especially in young, fast growing polyps. However, not only was net calcification maintained at water aragonite saturation <1, but acclimation to enhanced pCO_2 equivalent to pH reductions by 0.1 units led to calcification rates being maintained over six months (Form and Riebesell, 2012), likely due to upregulation of pH and carbonate saturation at calcification sites (McCulloch *et al*., 2012). The role of the aragonite saturation horizon in defining the distribution of cold water corals is thus not clear (Guinotte *et al*., 2006).

6.2.5.5. Sensitivities of Marine Reptiles, Mammals, and Birds to Climate Change

Long-term data sets indicate that some species of seabirds, marine mammals and sea turtles are responding to the anomalous ocean climate of the 20th century (Hughes, 2000). The reptiles, being ectotherms, are more responsive to temperature effects than seabirds and marine mammals (6.2.2). There is insufficient information to assess the risks for sea snakes or crocodiles. For turtles, poleward distribution shifts consistent with recent warming have been recorded in almost all marine groups. Decadal scale climate fluctuations affect their recruitment success and nesting abundance (Van Houtan and Halley, 2011), warming and abundance being inversely correlated in various species and regions (Chaloupka *et al.*, 2008; Mazaris *et al.*, 2009 b; Balazs and Chaloupka, 2004; Saba *et al*., 2007;

Broderick *et al*., 2001). Extreme weather causes nest flooding, considerably reducing hatching success (Van Houtan and Bass, 2007). Those capable of changing nesting sites (Fish and Drews, 2009; Hawkes *et al*., 2009) will be less impacted than those with high fidelity to nesting and foraging sites (Cuevas *et al*., 2008). During continued warming, modulated by changing rainfall (Santidrián Tomillo *et al*., 2012), turtle sex ratios may be skewed towards output of females, combined with higher egg and hatchling mortality (Fuentes *et al.,* 2009; Saba *et al*., 2012), earlier onset of nesting (Pike *et al*., 2006; Weishampel *et al*., 2004; Mazaris *et al.,* 2008), decreasing nesting populations (Chaloupka *et al.,* 2008) and shifts in dietary breadths (Hawkes *et al.,* 2009), leading to projected recruitment declines for, e.g. the leatherback turtles (Saba *et al*., 2012). Vulnerability due to shifting sex ratio alone remains unclear as nesting beaches have persisted with low production of male hatchlings over decades or longer (Broderick *et al*., 2000; Godfrey *et al*., 1999; Hays *et al*., 2003; Marcovaldi *et al*., 1997; Poloczanska *et al.,* 2009). The absence of sea turtles in certain regions may, however, be best explained by the temporal unavailability of food resources or strong thermoclines restricting their bottom foraging abilities (Braun-McNeill *et al.,* 2008; Gardner *et al.,* 2008).

Seabird range modifications probably caused by climate change were recorded in polar areas and the temperate zone of the North Atlantic (Grémillet and Boulinier, 2009). Northern-temperate species have shifted their ranges to higher latitudes (Robinson *et al.,* 2005; La Sorte and Jetz, 2010). Southward range expansion or population growth are reported in the southern hemisphere, (e.g. Dunlop 2001; Bunce *et al.,* 2002). Some species like the king penguin follow shifting foraging zones (Péron *et al*., 2012), others are affected by changing habitat structure like sea ice (e.g. the emperor penguin, Jenouvrier *et al*., 2012). Trans-hemispheric migratory seabirds such as the sooty shearwater *Puffinus griseus*, which spend the austral winter off the coast of California, probably shifted towards the central, equatorial Pacific waters, where increasing SSTs may have enhanced primary productivity and prey availability (Hyrenbach and Veit, 2003). Warming causes many bird species to breed earlier (Sydeman and Bograd, 2009). Extant high-latitude, cool-water species experience extended breeding seasons (Chambers *et al.,* 2005, 2011). Nevertheless, there is often no clear agreement (Heath *et al.,* 2009) whether those changes solely reflect ocean warming or a combination of human-induced climate change and natural variations or other synergistic factors like fishing pressure on seabirds' prey species, sea level rise and pollution (Heath *et al.,* 2009; Galbraith *et al.,* 2005; Votier *et al.,* 2005). Most of the changes in range shifts and seasonal activity involve shifts in trophic relationships. Seabirds with narrow geographic domains and limited phenotypic plasticity are expected to be more susceptible to climate change (Chambers *et al.,* 2005; Grémillet and Boulinier, 2009); even leading to the local extinction of populations (e.g. the Galápagos penguin *Spheniscus mendiculus*, Vargas *et al.,* 2007; and the marbled murrelet *Brachyramphus marmoratus*, Becker *et al*., 2007).

Predator-prey dynamics or impacts on specific habitats also shape the effects of climate change on the distribution, phenology and migration timing of marine mammals (Calambokidis *et al.,* 2009; Salvadeo *et al*., 2011). Some marine mammals shift their distribution poleward to follow the movement of their prey (Simmonds and Isaac, 2007). There is *medium evidence* and *agreement* suggesting that expected patterns may already be occurring, in case of dolphin, porpoise and whale species showing a northward shift in distribution (Salvadeo *et al.,* 2010; MacLeod *et al.,* 2005; Springer *et al*., 1999; Calambokidis *et al*., 2009; Moore and Barlow, 2011). As in birds, vulnerability is high for marine mammals with narrow geographic ranges and high habitat dependence. Examples are the critically endangered vaquita (*Phocoena sinus*) endemic to the Northern Gulf of California, which cannot move north because of the land barrier; or the polar bear (*Ursus maritimus*, Laidre *et al.,* 2008; Rode *et al.,* 2010, 2012) and the walrus (*Odobenus rosmarus*) that depend on sea ice as a platform for hunting, resting and giving birth. For polar bears, access to prey such as ringed seals has been disrupted by the later formation and earlier breakup of sea ice in the eastern Canadian Arctic. Seasonal migrants and ice-associated species in the Arctic (fin whale; minke whale, *Balaenoptera acutorostrata*; gray whale; killer whale, *Orcinus orca*, humpback whale, *Balaenoptera novaeangliae*; and bowhead whale, *Balaena mysticetus*) may benefit from the net loss of sea ice, due to better access to a pelagic-dominated ecosystem (Moore and Huntington, 2008).

6.2.5.6. Conclusions

Physiological knowledge indicates with *high confidence* that animals specialize on restricted temperature and predicts how the species-specific capacity for performance and associated energy turnover shape sensitivity to climate induced ocean warming, acidification and hypoxia, thereby supporting attribution of effects to climate

change. Increased food availability and sustained feeding capacity improve resilience (high confidence). Extreme temperatures surpassing the fringes of the thermal envelope cause local abundance losses, extinction and shifts in temperature dependent distribution ranges (*high confidence*). These trends are exacerbated by the growing influence of OA and hypoxia, leading to mechanism based projections of faster range contractions than with warming alone (*medium confidence*), however, quantitative conclusions have *low confidence*. The synergistic effects of stressors cause relative changes in the performance of interacting species and lead to shifts in species interactions and food webs (*limited evidence, medium agreement*). High sensitivities to OA are associated with low metabolic rates and functional capacities of marine animal species. Calcification rates in sensitive invertebrate groups including corals, echinoderms and molluscs decrease under OA, especially if combined with temperature extremes (*high confidence*). Polar species sensitive to warming will be marginalized, with no possibility for that fauna to escape to colder regions (*high confidence*), however, formal loss of a polar species has not been recorded yet. Some tropical species such as corals or ecosystems such as coral reefs exist close to their upper thermal limits. *Confidence* is *low* for direct attribution of changes in life history and population dynamics of marine mammals, birds and turtles to climate drivers. Conversely, *confidence* is *high* that climate effects on reptiles, birds, and mammals are mostly mediated through climate-dependent changes in habitat structure and food availability.

6.3. Trends in Biological Field Observations: Attribution to Climate Change?

Mechanistic knowledge (6.2) and long-term observations (6.1.2.-3) support attribution to climate change of impacts including: (i) changes in abundance and overall biomass, (ii) loss of habitat, (iii) changes in community composition and species richness, (iv) changes in species biogeographical ranges, (v) alterations to phenology and the frequency of events like exposures to extreme temperatures, (vi) changes in connectivity among populations and habitats (e.g. Carson *et al*., 2010) and (vii) propensity for change, including frequency and severity of waterborne diseases. For warming and hypoxia, effects are accelerated by exposures of organisms and ecosystems to shifting seasonal or even diurnal extremes and their frequency (*medium evidence* and *agreement*) (e.g. Pörtner and Knust, 2007; Diaz and Rosenberg, 2008). This may also apply to effects of anthropogenic OA (*low evidence* and *agreement*), as indicated by the detrimental effects of upwelling high CO_2 waters on oyster cultures in the Northeast-Pacific (Barton *et al*., 2012). This section analyzes how physical and chemical forces (6.1.1) shape biological responses in the field, as a result of their physiology (6.2). Modeling approaches and the resulting global projections are discussed under 6.5.

6.3.1. Contrasting Observations and Projections on Primary Production

Observations indicate significant alterations of net primary production (NPP) in the ocean when environmental controls are altered due to natural perturbations, shifts in ocean currents, volcanic eruptions and enhanced iron supply, as in high-nitrate low-chlorophyll (HNLC) waters of the NE Pacific (Hamme *et al.*, 2010). Climate variability can drive pronounced changes in primary productivity (Chavez *et al.*, 2011), such as during the El Niño to La Niña transition in Equatorial Pacific, when nutrient and trace element supply are enhanced (Chavez *et al.*, 1999). As outlined in 6.1.3. and 6.2.3., the limited temporal extent of the satellite datasets, and the contrasting evidence from satellite and field based time series data in low latitude waters lead to *medium confidence* that there has been a small but significant increase in global NPP over the last two decades, but this increase may be linked more closely to shifts in environmental variability than to climate change. At high latitudes, there is *medium confidence* based on *limited evidence* and *medium agreement* from satellite images and modeling studies of an observed trend of higher rates of NPP (6.2.3).

6.3.2. Temperature-Mediated System Changes

Temperature effects on ecosystems are built on organismal responses, direct or indirect via competing species or the foodweb (6.2.2) or via additional changes in the physical environment. Direct organismal responses include changes in distribution, abundance, phenology and body size, which are related to physiological responses that affect species' performances in growth and reproduction (6.2.2.-5). Marine ecosystems are also indirectly affected by temperature through changes in stratification, sea-ice extent and interactions with other drivers like OA and hypoxia

(6.3.3). Species responses to temperature depend on location, the respective climate regime and, potentially, local adaptation (6.2.2). Geographical shifts of marine species from similar locations vary (Genner *et al*., 2004; Perry *et al*., 2005; Simpson *et al*., 2011b) emphasizing that thermal window widths and associated thermal sensitivities are species- specific, related to mode of life, phylogeny and associated metabolic capacities (6.2.5). Differences between species-level changes affect community and ecosystem responses to temperature-mediated effects.

6.3.2.1. Species Abundance, Biogeography, and Diversity

There is *high confidence* that recent changes in abundance and distribution of marine species and the associated shifts in biomes and diversity patterns are resulting, at least partly, from temperature-mediated biological responses (Table 6-8). In pelagic systems (Box 6-1), plankton abundance is related to water temperature (6.3.1, Ch. 30). For example, data from the Continuous Plankton Recorder (6.1.3) in the Northeast Atlantic from 1960 to 1995 show that warmer temperature enhances phytoplankton growth (Edwards *et al*., 2001), and that plankton distribution in the North Atlantic shifted poleward at a mean rate of hundreds of km per decade since the 1950s (Beaugrand *et al.*, 2009; Beaugrand *et al.*, 2002; Bonnet *et al.*, 2005; Lindley and Daykin, 2005; Richardson *et al.*, 2006; Figure 6-11, Box 6-1). Coccolithophore blooms (*E. huxleyi*) were observed for the first time in the Bering Sea during the period 1997-2000, probably in response to a 4°C warming cue, combined with a shallower mixed layer depth, higher light levels and low zooplankton grazing (Merico *et al*., 2004). Warming may also have caused the southward movement of coccolithophores in the Southern Ocean in the 2000s (Cubillos *et al.*, 2007).

[INSERT TABLE 6-8 HERE
Table 6-8: Examples of observed biological responses resulting from temperature and temperature-mediated changes in the ocean.].

Similarly, the distribution of pelagic and demersal fishes and macroinvertebrates has shifted poleward at tens to hundreds of km per decade during warming since the 1970s, although the range shifts have not been uniform across taxa or ocean regions (Johns *et al.*, 2001; Johns *et al.*, 2003; Mackas and Beaugrand, 2010; McGinty *et al.*, 2011). In the Northeast Pacific, the center of distribution of forty fishes and invertebrates shifted north by an average of 34 ± 56 km since the early 1980s (Mueter and Litzow, 2008; WGII Ch. 28). A general increase in the frequency of southern species moving northward occurred with El Niño associated warming events in the late 50s, early 80s and late 90s and, with a general interdecadal climatic regime shift in the California Current, beginning in the late 70s (McGowan *et al.*, 1998). In the North Sea, marine species have been moving polewards by 22 km decade^{-1} and to deeper water by 3.6 m decade^{-1} in relation to warming from the 1970s to 2000s (Perry *et al*., 2005; Dulvy *et al*., 2008). A global meta-analysis including 311 marine species from non-single species studies estimated an average poleward shift of 8.9 km decade^{-1} (Przeslawski *et al*., 2012). These distribution changes are mostly attributed to temperature change, but may be influenced by other factors such as sea-ice extent, nutrient enrichment and overfishing. For comparison, average terrestrial species distribution shifts ranges from 6.1 km per decade (Parmesan and Yohe, 2003) to 16.9 km per decade (Chen *et al*., 2011), with a high diversity of range shifts among species. Shifts to cooler depths in marine environments are the equivalent of altitudinal shifts in terrestrial environments (Dulvy *et al*., 2008; Burrows *et al*., 2011). Poleward distribution shifts resulted in increased species richness in high latitude regions (Hiddink *et al*., 2008) and in changing community structure (Simpson *et al*., 2011), causing polar and temperate ecosystems to become more temperate and subtropical, respectively (Philippart *et al.*, 2011). In semi-enclosed seas such as the Mediterranean geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram *et al*., 2010), with associated niches filled by alien species, either from nearby or artificially introduced (Philippart *et al*., 2011).

[INSERT FIGURE 6-11 HERE
Figure 6-11: **A**. Long-term changes in the ecosystem state based on 5 biological parameters (phytoplankton colour index, mean size of calanoids, mean calanoid diversity, an index of change in plankton composition and cod recruitment). The orange line denotes the mean ecosystem state for the period prior and after the abrupt ecosystem shift. **B**. Long-term changes in the multiscale temporal local variance of the ecosystem state (in red). High values indicate pronounced year-to-year changes in the ecosystem state. The light gray band shows the unstable period (1980-1989). **C**-**D**. Observed mean annual sea surface temperature in the North Sea during 1960-1981 (**C**) and 1988-

2005 (**D**). The location of the critical thermal boundary (9-10°C) is indicated by '+'. **E.** Long-term changes in the mean number of warm-temperate pseudo-oceanic species from 1958 to 2005. **F.** Long-term changes in the mean number of temperate pseudo-oceanic species from 1958 to 2005. The period 1958-1981 was a period of relative stability and the period 1982-1999 was a period of rapid northward shifts, indicating that the abrupt ecosystem shift observed in the North Sea was part of a large-scale response of the zooplankton biodiversity to warming temperatures (see **A**-**D**). Average values are below 1 because they are annual averages. Note that the colour bar is 10-fold inferior for warm-temperate pseudo-oceanic species because these species are less frequently observed than their temperate counterparts. From Beaugrand *et al*. (2008) and Beaugrand *et al*. (2009).]

Field observations show changes in abundance, distribution and diversity of ocean benthos in response to climate change, especially in intertidal organisms and coral reefs (WGII Ch. 5, *robust evidence, high agreement*) but also in other benthos (*medium confidence*), shaped by exposures to temperature extremes (WGII Ch. 5; cf. Figure 6-7). Phenomena in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g. of the Mediterranean, Bianchi, 2007) on biogeographic boundaries (Poloczanska *et al.*, 2011). Considerable poleward shifts of warm water species including macroalgae (Table 6-8; van den Hoek, 1982; Müller *et al*., 2009, 2011; Fernández, 2011) or corals (Precht and Aronson, 2004; Yamano *et al*., 2011) have been observed over last decades (*high confidence*) and are projected to continue (Müller *et al*., 2009, 2011). In corals during the last interglacial this was paralleled by the equatorial deterioration and retreat of coral reef ecosystems (Kiessling *et al*., 2012), likely due to associated bleaching (6.2.5; Box CC-CR). This confirms that shallow-water reef-building corals and their low latitude ecosystems are among the most sensitive to warming (Veron *et al*., 2009). However, a large scale survey found diverse coral reef types along a climatic gradient, but no consistent latitudinal response to climatic drivers (Hughes *et al*., 2012). The distribution of sublittoral benthos may respond more slowly to warming than that of fishes, plankton and intertidal organisms, but immigration and proliferation of species from warmer waters has been observed in selected areas like the British channel (Hiscock *et al*., 2004; Hinz *et al.*, 2011) or the North Sea coastal area (Reise and van Beusekom, 2008). The diversity of these findings indicate various environmental influences and pathways of changing species composition.

6.3.2.2. Phenology

There is *robust evidence* from long-term observations that warming and other temperature-mediated changes have resulted in shifting phenologies of marine species (Table 6-8), ranging from phytoplankton and zooplankton blooms, to reproduction and migration of invertebrates, fishes and seabirds, with many biological events advanced in timing under warming. In the waters around the U.K., during a period of warming between 1976 and 2005, the seasonal timing of biological events of all major marine taxonomic groups (plant/phytoplankton, invertebrate and vertebrates) advanced on average, by 0.31 to 0.43 days year^{-1} (Thackeray *et al*., 2010). This rate of phenological shift is not statistically different from shifts observed for freshwater and terrestrial species. Overall, the average rate of shift across species in all biomes is estimated to be 0.39 d yr^{-1}. Patterns of phenology shifts are different between trophic groups, potentially causing trophic mismatch and disruption of interspecific interactions.

6.3.2.3. Body Size

There is *medium evidence* from long-term observations that warming and other temperature-mediated changes affect the body size of marine organisms (Table 6-8). Weight-at-age of some juvenile or younger fish populations were shown to increase with temperature, as warmer water increases growth rates (e.g. Brunel and Dickey-Collas, 2010; Neuheimer and Grønkjær, 2012). However, spatial and temporal comparisons of observed maximum body sizes of invertebrates and fish populations suggest a decrease in maximum body size as temperature increases (6.2.2., Box 6-1, e.g. Daufresne *et al*., 2009). Changes in body size observed in a local population under warming may be complicated by effects on energy budget through temperatures drifting outside of a species' optimum range, the availability and changing body size of prey, species interactions or effects of fishing (Cheung *et al*., 2012).

6.3.2.4. Trophic Interactions

There is *high confidence* that temperature affects marine trophic interactions through changes in the distribution and timing of peak abundances of prey and predator, their growth and consumption rates (grazing or predation; Table 6-8). A time series for four commercial fish species and their zooplankton prey in the Norwegian and Barents Seas showed that climate shapes population growth rates through complex influences early in life, including direct temperature effects on growth, further effects through prey and delayed feedback effects through predators (Stige *et al.*, 2010). In a study of temperature effects on five trophic levels, species interactions of primary producers (microalgae), primary, secondary and tertiary consumers (zooplankton, fishes and jellyfishes) and benthic detritivores (echinoderms and bivalves) were modified through trophic amplification due to differential species responses to temperature (Kirby and Beaugrand, 2009). There is *high confidence* that the responses of various plankton functional groups, diatoms, dinoflagellates or copepods to warming are not synchronous, resulting in predator – prey mismatches that carry over to higher trophic levels (Edwards and Richardson, 2004; Costello *et al.*, 2006; 6.3.5., 6.3.6). In the intertidal, the relative ranges of predator and prey change in response to warming lead to shifts in dominance through interactions and modifications in predator pressure (Harley, 2011).

6.3.2.5. Conclusions

Overall, there is *very high confidence* that temperature is directly affecting marine organisms, their biogeography and community structure in both pelagic and benthic systems. Effects are complemented by indirect effects, e.g. *via* stratification, sea ice melt and freshening (*high confidence*). In a warming world, ecosystems adapted to the coldest temperatures or existing at their upper thermal limits are more sensitive (6.2.5). Long-term field observations and experimental research have identified, with *high confidence* and building on *robust evidence* and *high agreement*, that shallow-water reef-building corals and their reefs are among the marine ecosystems most affected by climate change and especially associated warming. However, other factors change concomitantly, such that quantification of the fraction of ecosystem change attributable to temperature has not always been possible.

_____ START BOX 6-1 HERE _____

Box 6-1. The Atlantic Example: Long-Term Responses of Pelagic Organisms and Communities to Temperature

Long-term observations (6.1.3) encompassing the whole pelagic Northeast Atlantic over a 50 year period show changes in the seasonal abundance of phytoplankton and rapid northerly movements of temperate and subtropical species of zooplankton (e.g. calanoid copepods) and phytoplankton (e.g. dinoflagellates and diatoms) and changes in the ecosystem functioning and productivity (Edwards *et al.*, 2001; Beaugrand *et al.*, 2002; Edwards and Richardson, 2004). The range limit of warm water copepods shifted by 10° north since 1960 (Beaugrand *et al.*, 2009), with attendant mismatch in the seasonal timing of trophic levels and functional groups (Edwards and Richardson, 2004). Fluctuations in climate indices like the Northern Hemisphere Temperature (NHT) and the North Atlantic Oscillation (NAO) over multidecadal periods accompanied these changes. In cooler regions increased phytoplankton activity caused by warming probably favored growth and the observed increase in phytoplankton biomass, whereas a decrease in nutrient supply would have prevented growth in warmer regions and caused a decrease in biomass (6.2.3; Richardson and Schoeman, 2004). Hinder *et al*. (2012) attributed a recent decline in dinoflagellates in relation to diatoms to warming, increased summer windiness and thus, turbulence. In the Northwest Atlantic sub-polar region, shifts in plankton distribution may be limited by the prevailing flow from the north, in addition to sea-ice extent and temperature (Head and Pepin 2010).

In line with the increased understanding of physiology (6.2.2., 6.2.5) warming in the temperate to polar North Atlantic was paralleled by a reduction in the average body lengths of about 100 copepod species, from 3-4 mm to 2-3 mm. Warming also led to an increase in species richness among copepods and in the dinoflagellate genus *Ceratium* (Beaugrand *et al.*, 2010). For diatoms as major contributors to carbon export (Armbrust, 2009), warming and decreasing annual variability in SST were associated with lower diversity, smaller size and reduced abundance (Beaugrand *et al*., 2010). Morán *et al.* (2010) found that temperature alone explained 73% of the variance in the

contribution of small cells (picophytoplankton) to total phytoplankton biomass in the eastern and western temperate North Atlantic from -0.6 to 22°C. Global outbreak frequencies of jellyfish aggregations may follow rising SSTs (Mills, 2001; Purcell, 2005; Purcell and Decker, 2005), however, evidence is inconclusive. Some studies report an increasing trend (Brotz *et al*., 2012) and others do not support this view (Condon *et al*., 2013) (*low confidence).*

The ecosystem regime shift observed in North Sea plankton in the late 1980s involved an increase in phytoplankton and changes in species composition and abundance among holozooplankton (animals that are planktonic for their entire lifecycle) (Reid *et al.*, 2001; Kirby and Beaugrand, 2009; Kirby *et al.*, 2009; Lindley *et al.*, 2010). This North Sea regime shift was paralleled by the northward propagation of a critical thermal boundary (CTB) between the temperate and the polar biomes (Figure 6-1; Beaugrand *et al*., 2008). Surpassing the CTB led to pronounced and large-scale variations in phytoplankton productivity, an increase in calanoid copepod diversity (Beaugrand *et al*., 2008) and herring abundance (Schlüter *et al*., 2008), a reduction in the mean size of calanoids and a decrease in the abundance of Atlantic cod in the North Atlantic Ocean (Beaugrand *et al*., 2010). These patterns also extend to the Southern North Sea, where elevated salinities and average warming by 1.6°C both in summer and winter between 1962 and 2007 expanded the time window for growth of microalgae and possibly supported the invasion and increase in numbers of warm-adapted silicified diatoms (Wiltshire *et al*., 2010).

Regions of high vulnerability exist where mild warming can trigger rapid and substantial ecosystem shifts, offering a way to anticipate future shifts in all of the North Atlantic sector. Recent findings indicate a regime shift in the Bay of Biscay, the Celtic and the North Seas in the mid to end 1990s (Luczak *et al.*, 2011) when a shift in plankton composition and in the abundance of both sardine and anchovies and of the Balearic shearwater (*Puffinus mauretanicus*, an endangered seabird) paralleled stepwise warming. In contrast, changes in SST, plankton composition and productivity in the southern Bay of Biscay were less marked in areas influenced by seasonal upwelling (Valdés *et al*., 2007; Bode *et al*., 2009, 2011). In the North Sea, a further shift discovered at the end of the 1990s (Beaugrand *et al*., revised) impacted about 40% of the phytoplankton and zooplankton species and thus had the same magnitude as the North Sea regime shift in the 1980s.

Changes in local and regional species richness, abundance and community composition result from species-specific latitudinal range shifts, depth distribution and the associated change in the structure and functional properties of ecosystems, such as productivity, energy flows and invasion resistance (*high confidence*, Stachowicz *et al.*, 2002; Duffy, 2003; Simpson *et al*., 2011b). Similar to plankton, northward range extensions or redistributions in fishes were largest along the European Continental shelf and attributed to regional warming, e.g. by 1.05°C from 1977 to 2001 in the North Sea, with winter warming being effective for Atlantic cod (Perry *et al*., 2005; 6.2.5). In the Northwest Arctic winter and spring warming caused expansion of the thermal optimum area covering 4–8°C, associated with greater growth in Atlantic salmon (Friedland and Todd, 2012). Pelagic sardines and anchovies entered the North Sea in the early to mid 1990s, after about 40 years of absence, in response to intensified NAO and AMO (Alheit *et al.*, 2012). Red mullet and bass extend to western Norway, and Mediterranean and north-west African species extend to the south coast of Portugal (Brander *et al.*, 2003; Beare *et al.*, 2004; Genner *et al.*, 2004).

The cooling and freshening of the Northwest Atlantic during the late 1980-early 1990s had the opposite effect, causing capelin and their predator, Atlantic cod to shift farther south (Rose and O'Driscoll, 2002). Between the early 1990s and mid-2000s in the Northwest Atlantic sub-polar gyre, phytoplankton increased, due to warming induced stratification. At the same time Arctic copepod species became more abundant, due to increased influx of Arctic water (Head and Pepin, 2010). Although temperatures have risen on the Newfoundland Shelf (Colbourne *et al*., 2011), capelin and cod remain scarce throughout the region for reasons likely unrelated to climate (DFO 2011a,b). Further south, Arctic freshwater inflow caused freshening and associated stratification of the area around the Gulf of Maine, throughout the 1990s, resulting in enhanced phytoplankton abundance, a larger and later fall bloom, increased abundance of small copepods, and a decrease in the large copepod *Calanus finmarchicus* (de Young *et al*., 2004; Pershing *et al*., 2005, 2010). Various fish species showed poleward shifts in distribution (Table 6-8). This was associated with reduced survival of larval cod (Mountain and Kane, 2010), fewer right whale calves (Greene *et al*., 2003), but increased herring abundance (Greene and Pershing, 2007).

_____ END BOX 6-1 HERE _____

6.3.3. Effects of Hypoxic Events and Expansion of Oxygen Minimum Zones (OMZs)

Hypoxic or anoxic conditions in both water and sediments strongly impact marine biota (6.2.2). O_2 deficiency in expanding OMZs will shift pelagic communities from diverse midwater assemblages to diel migrant biota that return to oxygenated surface waters at night (Seibel, 2011). Expanding OMZs will cause habitat loss to groundfishes and pelagic predators, affect the distribution of key zooplankton and nekton species and influence their diurnal and ontogenetic vertical migrations (Auel *et al.*, 2005; Ekau *et al.*, 2010). Major effects of expanding OMZs thus are habitat compression or abundance losses for intolerant taxa such as billfishes and other pelagic fishes with a high O_2 demand (Prince and Goodyear, 2006; Prince *et al.*, 2010; Stramma *et al*., 2012; cf. 6.2.5), large benthic invertebrates like crabs (Chan *et al.*, 2008), mesopelagic fishes (Koslow *et al*., 2011) and groundfishes (McClatchie *et al.*, 2010). Hypoxia effects propagate along the food chain and thereby affect fish stocks and top predators (Stramma *et al.*, 2010). Conversely, hypoxia supports range expansions or population growth in tolerant taxa like anaerobic bacteria (Ulloa *et al*., 2012), gelatinous zooplankton (medusae, ctenophores) and selected fishes (gobies, hake), or possibly selected cephalopods (Gilly *et al.*, 2006; Zeidberg and Robinson, 2007; Bazzino *et al*., 2010), characterized by slow growth rates, low O_2 demand and high capacities to exploit available O_2. Overall, expanding hypoxia will result in a lower biodiversity (Levin, 2003; Levin *et al.*, 2009a; Ekau *et al.*, 2010; Gooday *et al.*, 2010).

Upwelling events can be associated with exposures to hypoxic high CO_2 deep water causing strong ecosystem responses (*high confidence*), such as hypoxia induced biomass reduction in fish and invertebrate fauna (Keller *et al.*, 2010) and increases in sulphide-oxidizing bacterial mats (Chan *et al.*, 2008). Shifts in upwelling activity with climate change coincide with an apparent increase in the frequency of submarine gas eruptions of methane and hydrogen sulphide, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic to anoxic sea floor (Bakun *et al.*, 2010). These eruptions and the combined factors acting have been blamed for extensive mortalities of coastal fishes and invertebrates (Bakun and Weeks, 2004) and reductions in fishing productivity, particularly of Cape hake (*Merluccius capensis)*, Namibia's most valuable fishery (Hamukuaya *et al.*, 1998).

Dissolved O_2, among other factors, plays an important role in shaping large alternating fluctuations of sardine and anchovy abundances, particularly off Peru. Anchovies are not strongly affected by a shallow oxycline (<10m), while sardines actively avoid such conditions (Bertrand *et al*., 2010). High susceptibility of early life stages to hypoxia in both pelagic and benthic ecosystems (Ekau *et al*., 2010), threatens population survival. In benthic ecosystems, the expansion of OMZs will, with *high confidence*, shift microbial and faunal composition, reduce diversity and alter the functional attributes of upper slope and shelf environments (Levin *et al.*, 2009a; Stramma *et al.*, 2010).

As CO_2 increases in parallel to O_2 depletion, marginalization of calcifiers is observed in OMZs (Levin, 2003), indicating interactions of hypoxia with acidification (6.2.2). Furthermore, significant correlations between H_2S concentrations and climate change indicators such as sea surface temperature and sea level pressure have been documented at interannual and interdecadal scales for the open part of the Black Sea (Daskalov, 2003; Faschuk, 2011). There is *medium confidence* that climate associated processes may change the parameters of anoxic and OMZs and of zones poisoned by hydrogen sulphide and thus influence corresponding pelagic and bottom faunal distributions, trophic relations, energy flows, and productivity (Figure 6-12).

[INSERT FIGURE 6-12 HERE
Figure 6-12: Schematic illustrating the principal mechanisms underlying the formation of hypoxic conditions and their biological background (modified from Levin *et al.*, 2009a; Levin and Sibuet, 2012). The buoyancy flux from fluvial discharges produces sharp density stratification at the base of the freshened layer (also valid for icemelt, high precipitation) near the surface and, hence, vertical mixing is greatly reduced. In consequence, the nutrient inputs from the river and the atmosphere accumulate in a narrow upper layer, leading to phytoplankton blooms. The enhancement of oxygen consumption due to respiratory catabolism of sinking organic matter results in hypoxic conditions of OMZs. Heating of the upper layer further increases stratification, while the wind-driven upwelling of hypoxic, nutrient-rich water from deeper layers adds to the formation of the oxygen minimum zone.]

With the expansion and enhanced variability of OMZs, both (dissimilatory) nitrate reduction and anaerobic ammonium oxidation (anammox) will cause enhanced loss of fixed nitrogen limiting oceanic primary productivity

(*medium confidence*). Water column denitrification and N_2 fixation are spatially and temporally variable (*limited evidence, low confidence*) suggesting that climate effects on these processes are *unlikely* to operate uniformly (Brandes *et al.*, 2007; Fernandez *et al*., 2011; Franz *et al*., 2012).

In conclusion, there is *medium confidence* that OMZ expansion is causing habitat loss to groundfishes and pelagic predators and affecting the distribution of key zooplankton and nekton species as well as influencing their diurnal and ontogenetic vertical migrations. There is *high confidence* that effects of OMZ expansion will propagate along the food chain. If O_2 levels decline and OMZs expand further, a community change toward hypoxia-tolerant fauna will occur in midwater (*high confidence*). The diversity of macroorganisms will decrease and, finally, higher marine organisms will disappear and heterotrophic microorganisms will dominate (*high confidence*).

6.3.4. Effects of Anthropogenic Ocean Acidification

The strongest evidence for effects of ocean acidification (OA) on ocean biology stems from short (h) to medium term (several months) perturbation experiments in the laboratory or, more recently, the field and the assessment of organism responses after exposures to elevated CO_2 levels (6.2.2.-5). The long-term progressive nature of anthropogenic OA over years, even centuries indicates that results obtained during such acute exposures may not be easily scaled up to effects on longer timescales. Depending on the organism studied and its generation time perturbation studies measure tolerance and acclimation, but rarely adaptation or natural selection.

At ecosystem level shell thinning in planktonic foraminifera was attributed to anthropogenic ocean acidification in Southern Ocean species (Moy *et al*., 2009) and to both anthropogenic OA and upwelling of CO_2 rich deep waters for planktonic foraminifera in the Arabian Sea (de Moel *et al.*, 2009) or for pteropods in the Southern ocean (Bednarsek *et al*., 2012; *limited evidence, medium agreement*). An eight year trend of (variable) pH decline in coastal waters and the observation of species replacements in communities associated with local pH dynamics support the projection of shifts from shelled species like mussels to fleshy algae and barnacles with acidification along the Northeast Pacific coast (*medium confidence*, Wootton *et al*., 2008). Otherwise, contributions of OA to climate-induced alterations in the field have not yet been clearly established, partly because OA is still early in the process and has a much smaller effect than other drivers like temperature. For example, declines in calcification reported in corals (De'ath *et al.*, 2009) were elicited by thermal extremes and associated declines in performance, but may include an as yet unclear contribution by OA. Species-specific declines in calcification were also correlated with average annual sea surface temperature but at different temperature ranges characterizing the respective reef (Carricart-Ganivet *et al*., 2012).

Field studies at the demographic/metapopulation level are presently limited to natural analogues (CO_2 vents; Kroeker *et al*., 2011; Fabricius *et al*., 2011), indicating losses in diversity, biomass and trophic complexity of benthic marine communities. These studies cannot fully project future changes.

6.3.4.1. Bacterial Communities and Nutrient Cycles

Existing studies on the effect of OA (either through reduced pH or increased CO_2) on autotrophic and heterotrophic bacterial production have provided inconsistent results emphasizing that these responses are still poorly known and complex. Microbes are characterized by large diversity and broad environmental adaptation and hence may respond to environmental challenges by exploiting such diversity via species replacements (Krause *et al*., 2012) which makes projections of their reaction to ocean acidification on an ecosystem level very difficult. Processes discussed are: (1) cellular elemental stoichiometry (C-N-P ratios, Riebesell, 2004; Fu *et al*., 2007), (2) rates of CO_2 and N_2 fixation (Riebesell, 2004; Riebesell *et al*., 2008; Hutchins *et al*., 2007; Hutchins *et al*., 2009), (3) rates of nitrification (Beman *et al*., 2011), and (4) changes in the proportion of dissolved to particulate photosynthate carbon production and the implied efficiency of the biological carbon pump (Kim *et al*., 2011; 6.4.1). Field experiments led to the projection that nitrification rates (ammonia oxidation to nitrite and nitrite oxidation to nitrate) of ammonium oxidizing bacteria and archaea will be reduced by 3–44% in response to pH decrements by 0.05–0.14 (Beman *et al.*, 2011). Such a decrease in pH corresponds to a rise in atmospheric CO_2 concentration by approximately 100 µatm as projected for the next 30 to 40 years (WG I AnnexII). The reported decrease in nitrification occurred regardless of

natural pH variability providing no evidence for acclimation of the nitrifiers to reduced pH, e.g. in upwelling areas. However, potential changes in cell abundance, for example, due to lower per cell nitrification rates could further decrease or restore, respectively, the total volumetric rate of nitrification. While effects have been observed in the laboratory and in coastal mesocosm studies (Weinbauer *et al*., 2011) or in field experiments (Beman *et al.*, 2011), there is no evidence as yet for a reduction in abundances or metabolic activities of microbial communities in the field at either extreme of extant pH variability (Joint *et al*., 2010). Krause *et al.* (2012) documented a change in composition, without loss in abundance for a coastal bacterial community at pH 0.4 and 0.5 below ambient for the North Sea. Liu *et al.* (2010) propose that the rates of several microbial processes will be affected by OA, some positively, others negatively. The potential of the microbial community to adapt to OA and maintain function, either by genetic change at the species level or through the replacement of sensitive species or groups at the community level, remains to be explored further such that projections of future changes are not yet possible.

6.3.4.2. Phyto- and Zooplankton Communities

While there is *high confidence* in systematic changes in plankton abundance and community structure over recent decades (6.1.2, 6.3.1), most of these changes were caused by both the direct and indirect effects of warming and are driven in many cases by climate variability (Chavez *et al.*, 2011). The specific effects of anthropogenic OA are much less clear. Physiological rates and growth of some groups benefit from "fertilization" by CO_2 and may gain predominance (Rost *et al.*, 2008; Hutchins *et al.*, 2009, Table 6-6). Such shifts may be influenced by light and nutrients (6.2.2). For natural phytoplankton assemblages there is *medium confidence* to date that NPP is stimulated by increased CO_2 concentrations (Riebesell *et al.*, 2008; Tortell *et al*., 2008b). As responses to elevated CO_2 may influence the competitive abilities of species, small differences in CO_2 sensitivity may lead to pronounced shifts in the dominance of species (Tortell *et al.*, 2008b, Beaufort *et al*., 2011).

Quantification of the calcite mass of the coccolithophore community in the present ocean and over the last 40 kyr revealed patterns of decreasing calcification with increasing pCO_2, which in large parts was attributed to shifts between differently calcified species and morphotypes according to carbonate chemistry (Beaufort *et al.*, 2011). The same study, however, also observed heavily calcified *E. huxleyi* morphotypes in upwelling systems characterised by low pH, a finding which highlights the complexity of assemblage-level responses. For example, a shift from 'overcalcified' to weakly 'calcified' coccolithophores *Emiliania huxleyi* at higher latitudes may not reflect effects on cellular calcification rates but a temperature-related shift in ecotype dominance (Cubillos *et al.*, 2007; 6.3.2). Due to the complexity in response patterns, an up-scaling of effects of calcification in coccolithophores from monospecific culture experiments cannot be achieved. Projections of OA impacts on phytoplankton become even more complicated by synergistic interactions with other drivers (Boyd, 2011; 6.3.5).

For zooplankton, field and laboratory studies lead to *medium confidence* that pteropods (planktonic molluscs with aragonite shells) at high latitudes will experience reduced calcification in response to OA until the end of the century (Orr *et al.*, 2005; Comeau *et al.*, 2009; Comeau *et al.*, 2010; Lischka *et al*., 2011; Bednarsek *et al*., 2012). This may have severe impact on Subarctic Pacific and Southern Ocean ecosystems as pteropods form an integral part of the foodweb as grazers and prey for fishes like pink salmon (Bathmann *et al.*, 1991; Armstrong *et al.*, 2005; Hunt *et al.*, 2008). The comparison of decreasing calcification and shell weight found in extant planktonic foraminifera exposed to elevated CO_2 (Bijma *et al.*, 1999; Russell *et al.*, 2004; Lombard *et al.*, 2010) with findings in historical specimens (Moy *et al*., 2009) and during glacial interglacial cycles (Barker and Elderfield, 2002) supports *high confidence* in projections of future reductions in net calcification in foraminifera.

6.3.4.3. Macrophytes and Macrofauna at Ecosystem Level

Laboratory studies (6.2.2., 6.2.4) suggest that most seagrasses and non-calcifying algae respond to OA by increasing growth and recruitment, while calcifying algae experience reduced productivity. In various animal phyla, sensitivity seems to be highest in early life stages or during critical transition phases in the life cycle (6.1.2., 6.2.2., 6.2.5.., Table 6-5). The wide range of responses among macrofaunal calcifiers in experiments (e.g. Ries *et al.*, 2009), in natural settings at volcanic CO_2 vents (e.g. at Ischia, Italy, Hall-Spencer *et al.*, 2008 and Papua New Guinea,

Fabricius *et al.*, 2011) and in mesocoms (Christen et al 2013) suggests a wide range of ecosystem level consequences. For example, diversity is lower and non-calcifiers increasingly outcompete calcifiers once pH falls to a mean of 7.8 to 7.7 with a loss of calcifiers around pH 7.2 (Christen *et al.,* 2013). Calcitic bryozoans replace coralline algae which have more soluble high calcite skeletons (Martin *et al.*, 2008), corals decrease calcification rates, seagrasses and non-calcifying algae gain competitive advantage (Fabricius *et al.*, 2011) and net calcification changes to dissolution. However, the high pH variability at natural sites with lower pH values than indicated by the average change (Hall-Spencer *et al.*, 2008; Porzio *et al.*, 2011) and recolonization of the seep areas by larvae from neighbouring areas with normal pH or during periods of high pH, limits the use of these sites for analogues of future OA. With *limited evidence* and, thus *medium agreement*, warming probably exacerbates CO_2 effects on communities at the warm edges of their biogeographical ranges and vice versa (6.2.2., 6.2.5). For cold-water corals experimental and observational findings suggest some resilience to OA (*low confidence*, 6.2.5). The reduction of salinity associated with freshwater input results in lower alkalinity, exacerbates OA and may thereby contribute to constrain the distribution of sensitive species further in estuaries or brackish oceans like the Baltic or in freshening polar oceans (6.1.1., *low confidence*, Miller *et al.*, 2009; Denman *et al.*, 2011). It remains to be explored whether organisms in ecosystems characterized by permanently elevated or fluctuating CO_2 levels (6.1.1), like upwelling areas and OMZs, have evolved a higher resistance to increased CO_2 levels than elsewhere.

6.3.4.4. Conclusions

Overall, *confidence* is *high* that ocean acidification will affect marine ecosystems for centuries. The severity of effects will depend on RCP emission scenarios followed and maximum CO_2 levels reached, but the severity of effects cannot be directly related to any scenario at present. Detection, attribution and projection of OA effects at ecosystem level, including large scale ecosystem functions and biodiversity, are limited by the nature and duration of existing laboratory, mesocosm and field studies. The diversity of responses observed in organisms (6.2.5) and communities remain qualitative at best and are fraught with *low confidence*. Thresholds beyond which effects will set in can be quantified only with *low confidence*. While lab and mesocosm experiments provide evidence for differential effects on interacting species, further studies need to explore how OA may change the composition of communities, impact food webs and affect higher trophic levels. Consequences for fitness, abundance, distribution and species interactions cannot be projected to date. Accordingly, *confidence* is *low* that OA will cause a stimulation of phytoplankton primary production overall in the oceans and is *low* to *medium* for the net stimulation of nitrogen fixation by phytoplankton. C*onfidence* is *medium* that CO_2 accumulation associated with OA will stimulate primary production in non-calcifying macrophytes and thus benefit their abundance, but discriminate against calcifying algae. *Confidence* is *low* to *medium* that differential sensitivities and associated shifts in performance and distribution will change the quality of predator prey relationships and competitive interactions.

6.3.5. Concurrent Community Responses to Multiple Drivers

Various environmental drivers will change concurrently, eliciting a variety of responses ranging from organismal physiology to the areal extent and boundaries of biogeographical regions. This complexity is often confounding the clear attribution of biological trends to individual or anthropogenic drivers (Parmesan *et al.*, 2011). Alterations in marine ecosystems worldwide (Pauly *et al.*, 1998; Oguz, 2007; Österblom *et al.*, 2007) have often been linked to human and especially fishing activities (Frank *et al.*, 2005; deYoung *et al.*, 2008; Jackson, 2008; Casini *et al.*, 2009), however, they may involve a contribution of climate variability and change. Table 6-9 provides an attempt to categorize these multiple influences on marine biota – including temperature, CO_2, dissolved O_2 and nutrient concentrations - (e.g. Sarmiento *et al.*, 1998; Matear and Hirst, 1999; Boyd and Doney, 2002; Ekau *et al.*, 2010) – or other human interventions, including the introduction of non-native species, overfishing, chemical pollution, or habitat destruction (Carlton, 2000). The drivers can act individually, or interactively with either synergistic (i.e. amplification of) or antagonistic (i.e. diminution of) effects. A recent metaanalysis of 171 experimental studies that exposed marine systems to two or more drivers identified cumulative effects that were either additive (26%), synergistic (36%), or antagonistic (38%) (Crain *et al*., 2008). Effects range from direct impacts of ocean warming on organismal physiology (Pörtner and Knust, 2007), to ocean acidification acting together with either warming,

hypoxia or salinity changes leading to complex large-scale synergistic influences such as on both coccolithophore calcite production and abundances under warming and elevated CO_2 (Feng *et al.*, 2009, Table 6-9).

Present day OA is developing more than 10 times faster than in comparable paleo-events (6.1.2; Ridgwell and Schmidt, 2010), when similar to today, OA coincided with warming and enhanced stratification of the oceans and, consequently, a stronger deoxygenation of deeper waters (Thomas, 2007; Gattuso *et al.*, 2011), making it again difficult to attribute changes to OA (6.3.5). Furthermore, ocean physicochemical conditions prior to each of those paleo-events were very different from the present situation. Nonetheless, the PETM (55 Ma) provides useful comparative information for plankton and benthic foraminifera (6.1.2). Insight into the fate of animals shows some of them are affected, however, causalities and patterns have not been clearly identified (*low confidence*). The Permian Triassic (251 Ma) displayed similar patterns of sensitivity across animal phyla as projected for marine animal phyla today (6.1.2., 6.2.5).

[INSERT TABLE 6-9 HERE
TABLE 6-9: Potential interactions between modes of anthropogenic forcing (environmental; harvesting; or complex; considering scales and velocity of change, frequency, intensity, and variability of events) on different levels of biological organisation. These interactions, from simple to complex, are illustrated with published illustrative examples, ranging from physiological studies (Pörtner and Knust, 2007) to modelling studies such as Griffith *et al.* (2011). E, O, and M denote studies using manipulation Experiments (lab or field), Observations, or Modelling approaches, respectively; note that there is an insufficient number of studies to assign a level of confidence to each of these findings "???" defines the bounds on our understanding of the relationship between forcing and its effect on organisational level.]

Many microbes in the surface ocean are simultaneously limited by, for example, nitrate and phosphate, cobalt and iron (Saito *et al.*, 2002; Bertrand *et al.*, 2007), or iron and irradiance (Boyd *et al.*, 2010; 6.2.2). Both synergistic and antagonistic effects of multiple drivers on upper ocean biota have been observed in shipboard and/or laboratory manipulation experiments (Boyd *et al.*, 2010), which may result from the interplay of such co-limitations with multiple factors changing (Folt *et al.*, 1999; Gruber, 2011). In phytoplankton warming under high CO_2, photo-physiological rates of the cyanobacterium *Synechococcus* were synergistically enhanced, whereas the cyanobacterial group *Prochlorococcus* showed no change (Fu *et al.*, 2007). Such differences may result in floristic phytoplankton shifts with the potential to restructure predator-prey interactions (Table 6-9). For example, the magnitude of CO_2 effects on growth, fixation rates or elemental ratios within single species is often strongly modulated by nutrient availability and light conditions (e.g. Zondervan *et al.*, 2002; Sciandra *et al.*, 2003; Fu *et al.*, 2007; Kranz *et al.*, 2010). As the co-limiting environmental factors vary between different groups, such as nitrogen fixers (e.g. Hutchins *et al.*, 2007; Kranz *et al.*, 2010), coccolithophores (e.g. Feng *et al.*, 2009, Rokitta and Rost, 2012) versus diatoms (Boyd *et al.*, 2010), the predictive capacity of climate change effects is currently limited (Boyd *et al.*, 2010). At ocean basin scale, modeling experiments of interactive environmental effects provide the most reliable projections to date. They mainly point to synergistic effects, such as those of reduced pH, hypoxia and/or warming. Projected OA effects involve altering the sinking particles (C:N ratio and/or reduced calcite content and slower sinking) and a knock-on effect on water column O_2 demand (Gruber, 2011).

For complex organisms like animals or higher plants, climate change also involves synergisms and antagonisms of both abiotic and biotic factors. As increasingly understood in animals, the main drivers mediating climate impacts on ocean ecosystems are intertwined in their impact on organisms and, conversely, are shaped by the responses of biota. Warming reduces O_2 solubility and enhances biotic O_2 demand. The critical oxygen threshold P_c rises in animals indicating reduced hypoxia tolerance (Nilsson *et al.*, 2010; Vaquer-Sunyer and Duarte, 2011). The consumption of O_2 generates hypoxia, introduces CO_2 and causes acidification (Millero, 1995; Brewer and Peltzer, 2009). O_2 deficiency, in turn narrows the thermal range of animals (Pörtner *et al.*, 2005). As a consequence, midwater mesopelagic and demersal fish stocks may decline with expanding hypoxia and loss of habitat in the North Pacific or California Current Ecosystem and throughout the Southern California Bight at rates much quicker than anticipated due to warming (Koslow *et al.*, 2011; McClatchie *et al.*, 2010)..Similarly, CO_2 constrains thermal windows, causing biogeographical range contractions, changing phenologies and changes in relative performance, affecting predator-prey relationships or competitive species interactions (Figure 6-7C). Knowledge largely builds on laboratory work (6.2.4.-5) leading to the projection that the narrowing of the thermal niche by CO_2 and hypoxia will

cause shrinking biogeographical ranges, (Figure 6-7). Conversely, CO_2 sensitivity is enhanced at thermal extremes. In OMZs, CO_2 has a protective effect and sustains time-limited hypoxia tolerance since it facilitates the reduction in energy demand (Reipschläger *et al*., 1997; Pörtner *et al.*, 1998, 2000). Regions influenced by river runoff and experiencing increased precipitation will see a shift from marine to more brackish and even freshwater species, with unclear consequences for the impacts of other drivers. Reductions in primary production reduce resilience at higher trophic levels causing changes in species interactions (Kirby and Beaugrand, 2009; Stock *et al.*, 2011; 6.3.5). The introduction of non-indigenous species, when supported by climate-induced shifts in competitive interactions, may provoke the displacement of ecotypes and shifts in ecosystem functioning, for example, in the Mediterranean Sea (Occhipinti-Ambrogi, 2007; Coll *et al.*, 2010; Costello *et al.*, 2010). A mechanistic framework, such as oxygen and capacity limited thermal tolerance (OCLTT) in animals (Pörtner, 2010, 2012), would support a comprehensive understanding of the integrated effects of multiple drivers on organisms and ecosystems.

At the level of animal communities synergistic or antagonistic effects of various drivers remain largely unexplored. Adaptation to climate zones and variability may co-define species sensitivities (6.2.2., 6.2.5). This includes the role of CO_2 and temperature in warm water coral reefs (6.2.2., 6.2.5). It also includes the role of light versus temperature in shaping seasonalities and species interactions, for example during latitudinal distribution shifts (Bradshaw and Holzapfel, 2010). In the Pacific, the complex interaction of climate variability (due to ENSO), warming ocean surface, shallowing mixed layer depth in relation to the positioning of the warm pool and its convergence with the Pacific Equatorial Divergence Province, linked to the associated aggregation of macrozooplankton and micronekton, may have contributed to the net eastward shift of skipjack tuna between 1985 and 2010 (Lehodey *et al*., 2011).

Complex interactions also characterize eastern boundary upwelling systems which cover 1% of the ocean surface area but account for about 11% of new production (Monteiro, 2010) and half of the world's commercial fish catches (Merrett and Haedrich, 1997). Understanding whether upwelling and climate change will impact resident biota in a synergistic or antagonistic manner is highly relevant for projections of climate impacts on these areas and their services to human society. Upwelling in a changing climate will have both beneficial and detrimental effects. Upwelling of hypoxic and acidified waters will combine with anthropogenic impact and negatively affect marine biota and ecosystem structure of the upper ocean. However, under projected scenarios of reduced upward supply of nutrients due to stratification (Steinacher *et al.*, 2010), upwelling of both nutrients and trace elements may become increasingly important in maintaining upper ocean nutrient and trace metal inventories. Upwelling areas may also increase nutrient content and productivity under enhanced stratification (Rykaczewski and Dunne, 2010). Upwelled and partially denitrified waters contain excess phosphate that may select for N_2 fixation (Deutsch *et al*., 2007; Deutsch and Weber, 2012), but field observations of N_2 fixation in these regions have not supported these predictions (Fernandez *et al*., 2011; Franz *et al*., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

Observational (Schwing and Mendelssohn, 1997; Demarcq, 2009) and modeling evidence (Bograd and Lynn, 2003; Snyder *et al.*, 2003; Di Lorenzo *et al.*, 2005) indicates increased alongshore upwelling favored by winds over recent decades, as a putative consequence of warming (Bakun, 1990). Some spatial heterogeneity exists as in some areas like the Iberian peninsula, decreased upwelling occurs (Lemos and Sansó, 2006). The productivity of most wind driven upwelling systems has increased during the last decade (Demarcq, 2009). Habitat compression may initially even enhance fisheries catches in coastal regions or tropical OMZs. Upwelling regions sit closer to thresholds for hypoxia and acidification effects where ecosystem states may shift. For example, changes in sea surface temperature in the California Current System have been linked to latitudinal shifts in faunal composition and fisheries regimes and habitat expansion or contraction for the distribution of some species like sardine and anchovies or Humbold squid (Lluch-Belda *et al.*, 2001; Lluch-Belda *et al.*, 2003; Checkley *et al*., 2009b; Zwolinski and Demer, 2012; 6.3.3), or recruitment changes of near-shore invertebrates. Changing the duration, frequency and magnitude of the upwelling were relevant to explain the dynamic of benthos (Iles *et al*., 2012) and fisheries (Rykaczewski and Checkley, 2008). The effect of climate change on upwelling systems through stronger winds, altered current patterns or enhanced OA remains debated (Chavez and Messie, 2009).

6.3.6. Biotic Interactions

Impacts of climate change on marine populations (6.3.1.-5) underlie alterations of species interactions, ecosystems structure and functioning, including changes in trophodynamics and the physical and chemical characteristics of biogenic habitats. Changes in climate and NPP can affect the entire food web structure (Figure 6-13; Utne-Palm *et al.*, 2010) and the different components of the ecosystems, including fish resources (Parsons and Lear, 2001; Brown *et al.*, 2010; Cheung *et al*., 2010), by altering predation, competition, and food availability. Climate-driven shifts in dominant trophic pathways have been documented for a variety of marine ecosystems (Kirby and Beaugrand, 2009; Moloney *et al.*, 2011), in some cases, these are irreversible (Jarre and Shannon, 2010). As a consequence of warming, consumer control of food web structure may result because respiration of heterotrophic zooplankton and bacteria responds more strongly to changing temperature than photosynthesis of autotrophic phytoplankton (Connor *et al*., 2009; Gross, 2009). Community reassembly under climate change might involve the mixing of ecosystems with strongly altered trophodynamics (Cury *et al.*, 2003; Parmesan and Matthews, 2005; Luczak *et al.*, 2011). Trophic amplification may then drive an ecosystem towards a new dynamic regime.

[INSERT FIGURE 6-13 HERE
Figure 6-13: Schematic diagram of a marine foodweb and the expected responses to climate change including ocean acidification. A coupled pelagic and benthic foodweb is typically structured by the body size spectrum of species. Warming, hypoxia and ocean acidification lead to biogeographical shifts, changes in species abundance and in the dynamics of trophic interactions. The foodweb resulting from climate change includes reductions in the body size of organisms, changes in species composition and the resulting reconfiguration of trophic linkages. Fishing generally removes large-bodied and vulnerable species and truncates the body size spectrum of the community. As a result, the detection and attribution of foodweb responses to climate change are strongly confounded by fishing effects. The arrows represent species interactions (e.g. between predator and prey or competition for food or space). Broken lines (boxes and arrows) indicate the loss of populations and trophic linkages due to climate change.]

There is therefore *high confidence* that climate change will affect biodiversity, with specific differences between biomes and latitudes (Figure 6-1; 6.5., Sala and Knowlton, 2006; Cheung *et al.*, 2009) and cause community reassembly in time and space (Parmesan and Matthews, 2005; Parmesan *et al*., 2011). Species may gain predominance and abundance (Occhipinti-Ambrogi, 2007) from fitness benefits due to temperature change (6.2.2) while others become less competitive or easier prey. Shifted geographical distribution of marine species, e.g. to higher latitude or deeper water cause changes in community composition and interactions (Hawkins *et al*., 2009; Simpson *et al*., 2011b; Harley, 2011; Hazen et al., 2012). Reassembly of species might involve the mixing of ecosystems and strongly alter their food web functioning (Murphy, 1995; Anderson and Piatt, 1999; Moloney *et al.*, 2011) through trophic cascades (Cury *et al.*, 2003; Parmesan and Matthews, 2005; Luczak *et al.*, 2011).

Many impacts of climate change on food webs resemble those caused by other factors such as fishing, pollution, eutrophication, hypoxia (6.3.3) and habitat change (Brander, 2007), suggesting that unambiguous attribution to climate remains difficult (Parmesan *et al*., 2011). Conversely, the anthropogenic factors can affect ecosystem responses to climate change. Fishing truncates the age and size structure of populations making them more dependent on annual recruitment (Perry *et al.*, 2010; Genner *et al*., 2010; Botsford *et al.*, 2011) and reducing their ability to buffer environmental fluctuations (Planque *et al.*, 2010). Both adult and larval fishes show greater variability in abundance in exploited than unexploited populations (Hsieh *et al.*, 2006; Hsieh *et al.*, 2008). Both warming (e.g. Molinero *et al*., 2005) and acidification (Richardson and Gibbons, 2008), or removal of top or competing predators (e.g. Richardson *et al*., 2009; Condon *et al*., 2012) are discussed as reasons causing large fluctuations in gelatinous plankton (e.g. jellyfish) populations. Trans-Arctic interchange of species that repeatedly happened in warm periods (Dodson *et al*., 2007) may occur again, facilitated by enhanced trans-Arctic shipping.

Analyzing impacts on key species provides insight into how individual components of a food web will respond to perturbations. However, projections of future states must include the complex food webs interactions that influence the species and system level responses, which affect stability and resilience of the overall ecosystem to change (Martinez *et al.*, 2006; Neutel *et al.*, 2007; Dunne and Williams, 2009; Romanuk *et al.*, 2009). There is no single approach currently available for any oceanic system that includes the complex links within and among ecosystems, biogeochemistry and climate that are needed to do projections of future states of marine food webs with the certainty

needed for management and science (Fulton, 2011; Moloney *et al.*, 2011), and thus there is *low confidence* in the quantitative projections of such changes (for further discussion see 6.5).

Impacts of climate change on species providing structural habitat and support to high biodiversity (i.e. ecosystem engineers) can also result in profound ecosystem alterations. Tropical corals are known to respond to ocean warming and acidification with a variety of potentially deleterious effects on the structure of the biogenic habitat, from increased coral bleaching and impeded calcification rates to increased rates of coral disease (6.2.5; Veron *et al.*, 2009; Veron, 2011). For other benthic ecosystem engineers such as tropical calcified algae, bryozoans, sponges, and tube-forming serpulid worms (Wood, 1999), deep-water or cold-water corals or sponges, the knowledge on climate impacts is much less. However, they rely on productivity in surface waters, making them vulnerable to any alteration in local productivity patterns and food flux associated with climate change. In conclusion, there is *high confidence* that severe stress as projected from increased temperature, hypoxia and ocean acidification will cause reduced performance and increasing mortality in ecosystem engineers. As the number of available studies is scarce, projections of any more specific climate change effects come with *medium* to *low confidence*.

6.3.7. Summary and Conclusions

Except for the attribution of detected climate change effects to temperature, only a few cases allow clear attribution to another driver (6.6). *Robust evidence* from various ocean regions demonstrates with *high agreement and confidence* that temperature governs the geography, diversity, development, reproduction, behavior and phenology of marine organisms as well as the composition of communities and the seasonal timing of relevant processes (phenology). Accordingly, hydro-climatic variability, with a contributing role of the warming trend, causes large-scale changes in the biogeography, abundance and community composition and structure of marine species (*very high confidence*, 6.2.2.-5., 6.3.2). With *medium evidence* and *agreement*, changes in community composition are associated with reduced body body size (6.2.5) and increased diversity in some groups. Individual examples show, with *high confidence*, the specialization of animal species on regional climate regimes and, conversely, their sensitivity to change. Due to differential species responses to temperature, species interactions across trophic levels can be modified through trophic amplification (*medium* to *high confidence*).

Expansion of OMZs in response to climate leads to community shifts which are clearly attributable to exacerbating hypoxia (*high confidence*). Effects of a progressive decline in O_2 levels and gradual effects on communities have been insufficiently explored. In contrast to effects of temperature and extreme hypoxia, very few ecosystem level changes were attributed to anthropogenic or local ocean acidification trends (shell thinning in planktonic foraminifera, local pH dynamics causing species replacements, *medium confidence*). Otherwise, concomitant trends of warming, O_2 depletion, OA and other drivers prevent clear attribution. With *low evidence*, *medium agreement* and thus *medium confidence* community reassembly and ecosystem mixing may lead to new ecosystem states through trophic amplification (*low confidence*). With *limited evidence*, but *high agreement* and thus *medium confidence* climate change can strongly interact with top down human interferences like fisheries or other forms of harvesting which then accelerate such changes. Non-linearities that can operate within an ecosystem make the understanding and projection of marine ecosystem trajectories under climate warming more difficult.

6.4. Human Activities in Marine Ecosystems: Adaptation Benefits and Threats

6.4.1. Ecosystem Services

Human societies benefit from resources and processes supplied by natural ecosystems, collectively called ecosystem services (e.g. WGII Ch. 5). These are products such as food, fuel and biochemical resources, climate regulation and biogeochemical processes such as CO_2 uptake and carbon storage and water purification, cultural services like recreational and spiritual opportunities or aesthetic enjoyment, and functions supporting all other ecosystem services, such as nutrient cycling, photosynthesis and habitat creation. Most components of the marine environment contribute to more than one major category of ecosystem service: for example, ocean primary productivity is classified as a supporting service, but it affects provisioning services via fisheries and mineral extraction, regulating

services via the global carbon cycle and climate regulation, and cultural services via the enjoyment of a healthy ecosystem.

Attributing and forecasting possible climate-change-mediated changes in marine ecosystem services and assessing their effects on human communities is challenging. This is due to the lack of long-term time-series data, the confounding effects from human activities, the multiple and sometimes overlapping roles of marine ecosystem components in contributing to human well-being, and the difficulty of measuring and assessing the services themselves in ways that are comparable among ecosystem service categories. Some of the challenges are also related to the difficulty of projecting how human communities will adapt to changing marine ecosystem benefits.

6.4.1.1. Food from the Sea

Fisheries provide over 1.5 billion people with almost 20 % of their average per capita intake of animal protein. This value ranges up to over 90% in some regions (Bell *et al.*, 2009; Garcia and Rosenberg, 2010). Total World marine capture fisheries catches stabilized in the mid-1990s at between 75 and 85 million tonnes (FAO, 2010). Marine aquaculture contributes over 63 million tons per year to seafood production, mostly concentrated in coastal areas and comprising primarily molluscs and crustaceans. The growth of this industry has decelerated, but is still considered to be a development opportunity and a strong need in regions such as Africa and Latin America (WGII Ch. 7.4.2.2).

Experience based on other anthropogenic impacts on marine systems, indicates with *high confidence*, that shifts in ecosystems and fisheries production will create significant sustainability and management challenges, particularly amongst countries with fewer resources and adaptive capacity (Allison *et al.*, 2009; Worm *et al.*, 2009; Cooley *et al*., 2012). Fish stock migrations due to warming (6.3.2) have resulted in shifting composition of fisheries catches (Pinsky and Fogarty, 2012; Cheung *et al*., subm) and may result in shifting stock distribution (Sebatés *et al*., 2006) with consequent changes in accessibility and fishing operations costs, straddling economic zones, perturbing international fishery agreements and causing excessive exploitation (Hannesson, 2007; Sumaila *et al*., 2011). Warming may have beneficial effects on fisheries productivity in some regions, such as the North Atlantic because of the poleward distribution shift of exploited species and changes in primary productivity (Arnason, 2007; Stenevik and Sundby, 2007; Cheung *et al*., 2010), or for some Pacific Islands due to eastward redistribution of tuna stocks (Lehodey, 2000; Lehodey *et al.*, 2010, 2011). Invertebrate fisheries and aquaculture appear most vulnerable to the impacts of OA (Barton *et al*., 2012).

The potential interactions between warming, OA and other human impacts such as overfishing may exacerbate the impacts on a wide range of ocean processes and services, including marine fisheries (Table 6-9), For example, over-exploitation of fish stocks and the altered demography (Planque *et al.*, 2010; Petitgas *et al.*, 2006) may reduce the capacity of fish populations to buffer changes in climate variability (Fromentin and Fonteneau, 2001; Hilborn *et al.*, 2003; Ottersen *et al.*, 2006), leading to unpredictable non-linear outcomes (WGII Ch. 7.5.1.1.3).

Nations that depend strongly on fisheries and have limited adaptive capacities (Allison *et al.*, 2009), including many low-latitude and small island nations, are particularly vulnerable to climate change and OA impacts (Allison *et al.*, 2009). This will be exacerbated if increases in the frequency and severity of extreme events (e.g. floods or storms) effect citizens by damaging infrastructure, homes, health, livelihoods or non-marine food security (Kovats *et al.*, 2003; Rosegrant and Cline, 2003; Adger *et al.*, 2005; Haines *et al.*, 2006). Economic losses in landed catch value and the costs of adapting fisheries resulting from a 2°C global temperature increase by 2050 have been estimated at US$ 10-31 billion globally, with countries in East Asia and the Pacific being the most affected (Sumaila and Cheung, 2010; Sumaila *et al.*, 2011). Globally, the impacts will partially depend on the flexibility and response capacities of food production systems (Elmqvist *et al.*, 2003; Planque *et al.*, 2011a); however, the specific implications for the fishing industry are still poorly known, as *confidence* in future projections of shifts in primary production and knock-on effects through foodwebs and into fisheries is *low* (Brander, 2007; 2009; Planque *et al.*, 2011b; Stock *et al.*, 2011). Management and socioeconomic challenges may also result from increasing stock fluctuations, although modelling exercises illustrate that in general, management issues have a greater impact on biological and economic conditions than climate change is expected to have (Eide and Heen, 2002; Eide, 2007; 2008; Merino *et al.*, 2010).

6.4.1.2. Other Provisioning Services

Opportunities for marine industries may arise or disappear as systems change. For example, reductions in marine biodiversity due to climate change and other anthropogenic stressors (Tittensor *et al.,* 2010), like OA (CBD, 2009) and pollution, might have an overall negative effect on the discovery of genetic resources from marine species useful in the pharmaceutical, aquaculture, agriculture and other industries (Arrieta *et al*., 2010), leading to a loss of option value from marine ecosystems. Climate change increases the demand for marine renewable energy such as winds and wave power, although ecosystem impacts of the respective infrastructure need to be considered (6.4.2).

6.4.1.3. Climate Regulation

Climate regulation refers to the maintenance of the chemical composition of atmosphere and oceans by organisms and chemical as well as physical processes (Beaumont *et al.*, 2007). For 800,000 years prior to 1800, the interplay of biogeochemical processes on land and in the ocean (Sigman and Boyle, 2000) have resulted in relatively stable levels of atmospheric CO_2 level (between 170 and 276 µatm; Siegenthaler *et al.*, 2005; Lüthi *et al.*, 2008). Even over the last millions of years, proxy data suggest maximum CO_2 concentrations of 400 µatm (Pagani *et al.*, 2010; Seki *et al.*, 2010). There is *high confidence* that the effect of climate change on marine biota will alter the magnitude of many, if not all of the regulatory mechanisms in which organisms play a key role, such as the balance between photosynthesis and respiration (Johnson *et al.*, 2010), the biological pump (Volk and Hoffert, 1985; Feely *et al.*, 2008; Falkowski, 1997), the modulation of greenhouse gases with high warming potential such as nitrous oxide (N_2O; Jin and Gruber, 2003; Law, 2008) and other climatically reactive gases such as dimethylsulphide (DMS; Vogt *et al.*, 2008). In the geological past, during the PETM (6.1.2) warming of the global ocean and acidification led to changes in phytoplankton composition and in significant biologically mediated feedbacks. In coastal regions, increases in weathering and the hydrological cycle, and hence in runoff from land, led to eutrophication of shelf regions and increased freshwater runoff (Sluijs and Brinkhuis, 2009), while concomitantly open ocean productivity decreased (Gibbs *et al.*, 2006). At the onset of the PETM decreased carbon isotopic gradients between surface and deep waters are interpreted to be a result of increased stratification, reduced nutrient supply and a less efficient biological pump (Zachos *et al.*, 2003). The benthic foraminiferal fauna suggests that there was no reduction in export production reaching the deep ocean, suggesting better organic carbon preservation due to lower O_2 conditions (Thomas, 2007). There is no evidence for decreased biological carbonate production despite higher atmospheric CO_2 levels during the PETM (Gibbs *et al.*, 2010; 6.1.2). Simulations from coupled ocean-atmospheric carbon cycle and climate models suggest that climate change may decrease global ocean NPP (*low confidence*, 6.5.1). Such changes in NPP are projected to lead to a decrease in the export of biogenic carbon to the deep ocean (Bopp *et al*., 2002; Boyd and Doney, 2002; Hashioka and Yamanaka, 2007), which can have a positive feedback on climate change (WGI Ch. 6). However, the effect of a changing climate on some potentially important feedbacks such as the ocean's biological pump cannot be reliably modelled, as many of the factors controlling the functioning of this pump are poorly understood (Figure 6-6).

6.4.1.4. Natural Hazard Regulation

Natural hazards are generally increasing alongside global warming, with floods and storm surges accounting for over two-thirds of the natural disasters affecting people (SREX). The role of natural ocean structures and organisms in reducing the effects of natural hazards has been undervalued. For example, empirical and modeling studies show that coral reefs contribute to buffering the impact of tsunamis (Fernando *et al.*, 2005; Kunkel *et al.*, 2006; WGII Chs. 5, 30). Field and laboratory experiments and climate models indicate that climate change and OA may slow coral growth by nearly 50% by 2050 (Hoegh-Guldberg *et al.*, 2007; WGII Ch. 5). With *high confidence* anthropogenic climate change including OA that threaten coral reefs will make some islands and coastal areas more vulnerable with respect to tsunamis, as well as storm surges. Similar to coral reefs, wetlands and mangroves provide biologically diverse buffer zones that protect coastal regions from storm surges and wave activity (WGII Ch. 5), The impacts of OA and other climate related changes as well as pollution, deoxygenation and other overlapping stressors

on mangroves or wetlands have not been determined (Cooley *et al*., 2009; Cooley, 2012), and some of these stressors enhance each other's effects (Cai *et al*., 2011; Howarth *et al*., 2011; Feely *et al*. 2010).

6.4.1.5. Cultural Services

Recreation and support of tourism can be economically assessed using indirect valuation methods, but other cultural services relating to spiritual and heritage issues are extremely difficult to assess. Nevertheless, cultural services are often cited by coastal users as primary reasons for preservation. Marine biodiversity is an important component of ecosystem services, including cultural services. In many tropical countries, coral reefs and their enormous biodiversity sustain substantial tourist industries that attract millions of SCUBA divers every year. Annual net benefits from global reef tourism amount to about US$ 9.6 billion (Cesar *et al.*, 2003; Box CC-CR). If degradation of cultural ecosystem services occurs because of climate change, coastal visitors could choose to spend their recreational budgets on terrestrial attractions (UNWTO, 2008). New tourism opportunities could arise as people travel to see disappearing ecosystem types (e.g. Antarctic tourism, Liggett *et al.*, 2011) or newly open previously inhospitable areas as peak seasons shift (e.g. Amelung *et al.*, 2007; Moore, 2010) or as the locations of key attractors shift (e.g. cetaceans, Lambert *et al.*, 2010), but these opportunities seem short-lived and unsustainable.

Many cultures depend on spiritual and aesthetic benefits from marine ecosystems. While environmental change endangers harvests of culturally important species, cultural forces are putting simultaneous pressure on indigenous traditions, raising ethical questions about cultural preservation (e.g. Nuttall, 1998). In less remote coastal communities, aesthetic benefits from marine ecosystems influence economically measurable factors, such as the relationship of better water quality and lower instances of harmful algal blooms with higher real estate prices and shellfish landings (Jin *et al.*, 2008). Impacts of climate change on coastal habitats (Ch. 5) affect the aesthetic benefits of wetlands, sandy beaches and, in general, natural coastlines.

Heritage benefits of preserving marine ecosystems are extremely difficult to assess. Not only is the challenge because some heritage benefits will be enjoyed by future generations who derive economic benefits from a healthy, diverse ecosystem, but it is also because losses are presently being avoided by maintaining a bank of resources that could be tapped if needed. For example, the research and conservation value of coral reef biodiversity and its non-use value are estimated together at US$ 5.5 billion annually (Cesar *et al.*, 2003). Any biodiversity loss or pollution of marine ecosystems would decrease the benefits associated with the "insurance policy" of having untapped resources and those associated with the legacy of offering healthy systems to future generations. As with spiritual and aesthetic benefits, maintaining heritage benefits poses challenges for managers who have to consider present-day issues of equity and ethics as well as multigenerational (and possibly multi-cultural) ethical questions.

6.4.1.6. Supporting Services

These services form the foundation of all other ecosystem services. Identifying all supporting services in the marine environment is virtually impossible, as they are so diverse in nature and scales. However, potential changes in marine ecosystems due to climate change and OA can highlight the role of organisms and processes that are especially important in providing supporting services. For example, damage to calcifying algae and corals will reduce habitat for other marine species (6.3.5) and the biodiversity they sustain, the cultural and leisure values of these landscapes and their climate regulation capacity. The provision of open waterways for shipping is a specific supporting service that is expected to change in measurable ways in the next several decades (WGII Ch. 30.6.3.3). Reductions in sea ice in the Arctic may allow new trade passages such as the North West Passage to be established (Wilson *et al.*, 2004; Granier *et al.*, 2006), thereby raising the possibility of economically viable trans-Arctic shipping, as well as increasing access to regional resources supporting natural resource extraction and tourism. Accompanying the positive aspects of this development are negative consequences as well, such as increasing emission of greenhouse gases and other pollutants (Lauer *et al.*, 2009; Corbett *et al.*, 2010), and more potential for invasion of non-indigenous species due to hulls and ballast waters (Lewis *et al.*, 2004).

6.4.1.7. Conclusions

Human societies benefit from and depend on ecosystem services, including the provisioning of food and other goods, climate and natural hazards regulation, cultural and supporting services (*high confidence*). Attributing and projecting their climate-change-mediated shifts remains a challenge, partly because of the intrinsic difficulties of assessing these services, lack of long time-series data and confounding human impacts. However, available evidence from empirical and modeling studies provides *high confidence* that climate change impacts marine ecosystems, leading to changes in provision, regulation and supportive services, while there is *limited evidence* and *medium agreement* that climate change affect cultural services. Food production from the sea is already facing diverse stressors, such as overfishing and habitat degradation, which are expected, with *high confidence*, to interact with climate change phenomena, including temperature rise (6.3.2), ocean deoxygenation (6.3.3), and ocean acidification (6.3.4), causing significantly negative effects in particular to developing nations in tropical regions. The more northerly (and developed) nations may benefit from climate change, at least initially. There is *medium evidence* and *agreement* that climate change is affecting capture fisheries, although projections of such impacts into the future have *low confidence* partly because of the *low confidence* in marine primary production (6.5). Based on evidence from the geological past (*robust evidence*) and the present data (*limited evidence*), there is *high agreement* and *confidence* that marine ecosystems regulate climate through mechanisms such as the biological pump, the balance between photosynthesis and respiration and modulation of greenhouse gases. There is *high confidence* that the effect of climate change on biota will alter the magnitude of many, if not all of these processes. Projections on the direction and magnitude of specific biotic feedbacks to climate change are presently at an early stage of development and have l*ow confidence*.

6.4.2 Management-Related Adaptations and Risks

6.4.2.1. Ecosystem Management

Biophysical and socio-economic effects of climate change will pose new questions and elicit new strategies in the already highly demanding enterprise of managing ocean resources (Eide and Heen, 2002; Eide, 2007). There is *high confidence* that a changing climate will have both positive and negative socio-economic and geopolitical consequences affecting the future management of ocean resources (6.4.1). Ecosystem-based management (EBM), or the ecosystem approach (EA), is already being increasingly adopted globally (FAO, 2003) to deal with the multitude of human pressures on marine ecosystems (Sherman *et al.*, 2005; Hoel, 2009). Extended EBM would include climate-driven changes, as well as new human activities, as the many different drivers will interact and confound each other (Planque *et al.*, 2010; Eero *et al.*, 2011). Such an extension and integration (Miller *et al.*, 2010) is based on *high confidence* that the effects of different human activities will undermine resilience to other, including climate impacts or the effectiveness of mitigation and adaptation measures, by increasing variability (and reducing predictability), and limiting scope for adaptation (e.g. Hughes, 2004; Eero *et al.*, 2011; Sissener and Bjorndal, 2005). Thus, managing ecosystems under climate change requires increasing the resilience of the ecosystems and adaptive capacity of management systems through reducing other human perturbations (e.g. overfishing) (Brander, 2008).

Climate change effects cannot be completely mitigated by reducing the impacts from other non-climate drivers, highlighting the need for adaptive management accompanied by the detection and attribution of climate change impacts. Increased variability of ecosystems and the low predictability of some biological responses under climate change undermine the effectiveness of existing ocean management and conservation measures. Particularly, climate change may contribute to large-scale ecosystem regime shifts. Although there is potential for the early detection of ecosystem shifts through analysis of time-series of environmental and biological data (Carpenter and Brock, 2006; deYoung *et al*., 2008), long-term forecast of a regime shift is limited by an insufficient number of observations and limited quantitative understanding of regime shifts. In addition, biogeographical shifts under climate change (*high confidence*, 6.5) present direct challenges to the objectives of spatial management, which has become a fundamental part of EBM (Douvere, 2008). This does not invalidate the use of spatial management, but it does mean that “fixed in law forever” site attached zoning to protect specific species may need to become more flexible to ensure that the original objectives are maintained as species move or community structure shifts (Soto, 2001; Hawkins, 2012).

6.4.2.2. Geoengineering Approaches

Recent comparative assessments suggest that the main geoengineering approaches involving the oceans may have large associated environmental footprints (Boyd, 2009; Russell *et al.*, 2012). These geoengineering approaches include, Carbon Dioxide Reduction (CDR), Solar radiation management (SRM) and other similar approaches (see Table 6-10; IPCC, 2012). CDR removes atmospheric CO_2 by directly sequestrating it into the ocean (Boyd, 2008; Shepherd *et al*., 2009). SRM relies on causing increased albedo, for example via stratospheric sulphur injection (Crutzen, 2006). SRM may reduce warming and cause changes in precipitation and their impacts on ecosystems. The use of SRM is fraught with the shortcoming that CO_2 release and OA are left unabated unless SRM is combined with CO_2 emission reductions or CO_2 removal. Also, the sudden cessation of SRM after its implementation would exacerbate the climate effects on ecosystems (Russell *et al*., 2012).

[INSERT TABLE 6-10 HERE.
Table 6-10: Challenges for the oceans that will arise from the employment of a range of geoengineering methods (SRM, solar radiation management, CDR, carbon dioxide removal).]

CDR techniques involving the ocean include fertilization by nutrient addition, binding of CO_2 and build-up of DIC by the addition of alkalinity and direct CO_2 injection into the deep ocean (Table 6-10; Williamson *et al*., 2012), all of which have potentially negative consequences for marine ecosystems. Ocean fertilization through the addition of iron to high-nutrient low-chlorophyll (HNLC) oceanic waters would increase the net export of organic material to the deep ocean and its coupled decomposition, thereby causing deep water CO_2 accumulation. A further issue with fertilization is that it would affect all major biogeochemical cycles of the ocean with as yet unclear side effects, including the formation of methane (CH_4) and N_2O (Law, 2008) or the stimulation of harmful algal blooms (Trick *et al*., 2010; Silver *et al*., 2010). Enhanced NPP by ocean fertilization would add more carbon to the base of food webs (de Baar *et al.*, 2005) and stimulate growth of, e.g. deep-sea benthos (Wolff *et al*., 2011). The increase in organic material in an ocean region (through fertilization or storage of biomass) may cause enhanced O_2 demand and deep-water O_2 depletion (Sarmiento *et al.*, 2010; Table 6-10), which can add to the increase in level and extent of hypoxia and, consequently, their impacts on marine ecosystems (6.2.2., 6.2.5., 6.3.3., 6.3.5). The synergistic effects of hypoxia and hypercapnia will further exacerbate the biological impacts (*high confidence*). The addition of alkalinity e.g. calcium oxide, to neutralize the increased acidifying water would involve large-scale mining and their consequences on land. The biological effects of enhancing Ca^{2+} ions and dissolved inorganic carbon during alkalization remain insufficiently explored. Direct injection of CO_2 into the ocean and, especially, its localized disposal (deep-sea lake option) causes local effects of CO_2 and associated acidification on deep-sea organisms (6.2.2., 6.2.5., 6.3.4., *high confidence*, Caldeira *et al.*, 2005) but appear less harmful on larger scales than the combined impacts of hypoxia and acidification caused by ocean fertilization (Pörtner *et al.*, 2005; 6.3.3).

6.4.2.3. Health Issues

Human health may be directly impacted by harmful algal blooms (HABs) or the spreading or redistribution of disease vectors. HABs are mostly a natural phenomenon (Dale *et al.*, 2006), although biogeographical range extensions caused by regional climate change may have increased the regional presence of HABs (Edwards *et al.*, 2006), posing a major threat to the functioning of near-shore ecosystems. Range expansion of HABs can be related to warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas and enhanced surface stratification, which all have species-specific responses e.g. causing shifts in seasonal cycles and blooms (Johns *et al.*, 2001) or increased HABs as in the North Sea (Smyth *et al.*, 2004; Edwards *et al.*, 2006). For nearshore waters, analysis of both planktonic time-series archives and sediment cores, which record HAB cysts, have revealed few examples of strong linkages between altered HABS and climate change (Dale *et al.*, 2006). OA may exacerbate the toxicity of species contributing to HABs in coastal oceans under nutrient limited conditions (Tatters *et al*., 2012; Sun *et al*., 2011). Overall, there is *limited evidence, low agreement* and *low confidence* in how global climate change will impact HABs. However, because of the potential impacts of HABs on human health and different ecosystem services, adaptation measures of human societies have been suggested to include appropriate monitoring of increases and range extensions of biotoxin problems (Hallegraeff, 2010).

Climate change may drive changes in the abundance or distribution of pathogen species (Hoegh-Guldberg and Bruno, 2010), although attribution to climate change is confounded by climate variability and non-climate drivers (Lafferty 2009; Dobson, 2009). Specifically, the distribution of the waterborne bacterium, *Vibrio cholera*, the causative agent of cholera, may be supported by climate change. *V. cholera* is a marine bacterium that associates with marine organisms, especially chitinized zooplankton (Vezzulli *et al.*, 2010). Climate variability can affect the marine host species, and consequently the levels of the pathogen in coastal marine environments. In regions where cholera is endemic (e.g, India, Bangladesh, Latin America), cholera outbreak is correlated with elevated sea water temperature and zooplankton blooms (Lobitz *et al.*, 2000; Lipp *et al.*, 2002). Based on an 18-year climate record for Bangladesh, Pascual *et al.* (2000) reported an interannual component of cholera outbreaks at the dominant frequency of El Niño-Southern Oscillation (ENSO), and the recent reappearance of cholera in Peru has also been linked to the intense 1991-1992 El Niño event (Lipp *et al.*, 2002). There is evidence that an increase in sustained maximum surface temperatures of the temperate Baltic Sea is related to an increase in reported *Vibrio* infections (Baker-Austin *et al*., 2013). Continued warming of coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, sea water inundation due to sea level rise and ocean warming in temperate zones are all projected to exacerbate the expansion and threat of cholera (*limited evidence, low confidence*).

The risk of ciguatera-poisoning from seafood consumption is also related to ocean warming. Ciguatera-poisoning may occur when people consume fish, mainly from tropical reefs, that has bioaccumulated ciguatoxins due to exposure to the epiphytic dinoflagellate *Gambier discus* sp. Based on historical records, significant correlations have been reported between fish poisoning and sea surface temperature in South Pacific nations (Hales *et al*., 1999); however, such relationship is non-linear and dependent on the specific thermal window of the specific dinoflagellate (Llewellyn, 2010). Thus any scenario of an increase in ciguatera-poisoning under ocean warming based on linear extrapolations of observed phenomena has *low confidence*.

6.4.2.4. Conclusions

There is *high confidence* that the already challenging task of managing the oceans, their resources and linkages to human societies, will face new questions and difficulties due to the impacts of climate change on marine ecosystems. Fisheries and ecosystem management in the future might have to deal not only with the traditional sustainability goals, but might also have to increase ecosystems resilience to climate variability and change. Active ocean manipulation strategies to amend climate change may prove detrimental for different aspects of the ecosystems, which highlights the need for further research. There is strong interest in elucidating the potential changes of different human health issues related to direct exposure to toxic organisms and pathogens or to the ingestion of marine organisms that have bioaccumulated toxins. However, there is *limited evidence* and *low confidence* on how harmful algal blooms and the prevalence of pathogens will respond to climate change.

6.5. Future Projections of Climate Change Impacts through Modeling Approaches

A range of models are applied to explore climate change effects on marine biota, from primary productivity through to higher trophic levels, and to test hypotheses about responses of marine species, food webs and ecosystems (Rose *et al.*, 2010; Stock *et al*., 2011; Fulton *et al.*, 2011). Models range from empirical approaches to mechanistic models describing population/species responses and/or trophic interactions in marine ecosystems over a range of temporal and spatial scales (Barange *et al*., 2010; Stock *et al*., 2011). Earth System Models that couple atmosphere and ocean as well as climate and carbon cycles project changes in ocean biogeochemistry under a range of CO_2 emission scenarios (WGI Ch. 6). Models that focus on population and species level responses to environmental changes include population dynamic models, species distribution models and models which explicitly link climate change effects from changes in ocean physical and chemical conditions to the interactions between species at different trophic levels and human activities such as resource extraction and aquaculture (Rose *et al*., 2010). Uncertainty in model projections of changes in marine ecosystems is partly contingent on the level of confidence in climatic and oceanographic projections (6.1.1; WGI). Models are currently useful for developing scenarios of directional changes in net primary productivity, species distributions, community structure and trophic dynamics of marine ecosystems,

and their implications for ecosystem goods and services under climate change. However, quantitative projections from these models have *low confidence* (Rose *et al.,* 2010; Hannah *et al.,* 2010; Stock *et al*., 2011).

6.5.1. Ocean Primary Production

The long-term average of global ocean net primary productivity (i.e., NPP) is projected to change with climate, with large variations in the magnitude, direction and pattern of projected changes because of differences in model structure and parameterization (Figure 6-14). Four global coupled climate-ocean biogeochemical Earth System Models (WGI Ch. 6) projected an increase in NPP at high latitudes as a result of alleviated light and temperature limitations particularly in Northern and Southern Hemisphere 'subpolar gyre' biomes (Steinacher *et al*., 2010). However, the increase is more than offset by decreases in primary productivity in the North Atlantic, the tropics and the permanently stratified oceans at mid-latitude due to the reduced input of macro-nutrients into the euphotic zone. Reduced mixed layer depth and slowed circulation cause a decrease in macronutrient flux (Polovina *et al*., 2011; Figure 6-14). These result in a reduction in global mean NPP by 2 to 13% in 2100 relative to 1860 under a high emission scenario (SRES A2, between RCP6.0 and RCP8.5). This is consistent with projections from a more recent analysis that is based on 10 Earth System Models (Bopp *et al.*, subm). The study shows consistent decreases in global NPP that amount to -8.6 (±7.9), -3.9 (±5.7), -3.6 (±5.7), -2.0 (±4.1)% in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5 and RCP2.6, respectively. However, the magnitude of projected changes in global NPP varies widely between models (e.g. from 0 to 20% decrease in NPP globally under RCP 8.5). Main reasons for such variations include differences in parameterizations and assumptions between models. In contrast, earlier model projections show changes in global NPP from a decrease of > 10% (Field *et al.*, 1998; Boyd and Doney, 2002) to a slight increase by up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0) (Sarmiento *et al*., 2004; Schmittner *et al*., 2008). These projections do not consider the potential contribution of primary production derived from atmospheric N_2-fixation in tropical and subtropical regions, favored by increasing stratification and reduced nutrient inputs from mixing, although this burst in N_2-fixation is not sustainable without phosphate (e.g. Moore *et al*., 2009; Boyd *et al*., 2010). This may lead to an underestimation of primary production (Mohr *et al*., 2010; Mulholland *et al*., 2012; Wilson *et al*., 2012), however, the extent of such underestimation is unknown (Luo *et al*., 2012). Also, uncertainties in the accuracy of NPP observations further increase the uncertainty of projections, particularly from empirical models (e.g. Sarmiento *et al*., 2004; see 6.1.3). Furthermore, the potentially incomplete understanding of the effects of multiple drivers such as ocean warming, deoxygenation and acidification on NPP renders future projections uncertain. Changes in NPP have direct and indirect implications for higher tropic level organisms and fisheries (6.2., 6.4., 6.5.2., 6.5.3).

[INSERT FIGURE 6-14 HERE
Figure 6-14: Multi-model mean changes of projected vertically-integrated net primary production (small and large phytoplankton). To indicate consistency in the sign of change, regions are stippled where all four models agree on the sign of change. Changes are annual means under the SRES A2 scenario (between RCP6.0 - 8.5) for the period 2080 to 2099 relative to 1870 to 1889, after Steinacher *et al*. (2010).]

6.5.2. Higher Trophic Levels

Projected future changes in physical and biogeochemical conditions of the ocean are expected to affect the distribution and abundance of marine fishes and invertebrates (Figure 6-15). In the global ocean, driven by projected changes in temperature and other physical and chemical oceanographic factors, latitudinal distributions of 1066 species of exploited marine fishes and invertebrates are projected to shift by a median of around 50 km per decade (range limits) to higher latitudes by 2050 relative to 2000 under the SRES A1B (RCP6.0) scenario (Cheung *et al.,* 2009), Some species are projected to shift towards the equator following a regional temperature gradient (Burrows *et al*., 2011; Cheung *et al.*, 2012a). The rate of range shifts is projected to be three times higher for pelagic than for demersal fishes (Cheung *et al*., 2009), with demersal fishes shifting at a rate of around 25 – 36 km per decade (Cheung *et al.*, 2012a). The expansion of hypoxic waters may, however, have a greater impact on demersal fishes than warming (Koslow et al 2011). As a result of distribution shifts, high latitude regions (the Arctic, Southern Ocean) are projected to have high rates of species invasions. Intermediate latitudes are expected to experience both

invasions and local extinctions. High rates of local extinction are projected for the tropics and semi-enclosed seas (e.g. Mediterranean Sea, Persian Gulf). The global pattern of distribution shifts is generally consistent with regional-scale projections and past observations (e.g. Lenoir *et al*., 2011; Cheung *et al*., 2012b). However, detailed quantitative projections are sensitive to model structure and assumptions (Hare *et al*., 2012; Jones *et al*., 2013). Also, responses of specific populations may differ from average responses at species level (Hazen *et al*., 2012).

[INSERT FIGURE 6-15 HERE
Figure 6-15: Scenarios of climate change effects on the biogeography, biology and fisheries catch potential of marine fishes and invertebrates. (A) Hypothesis of changes in distribution, biology and fisheries catch potential of fish stocks under climate change. (B) Example of a projected rate of shift in distribution range along latitude and depth for 610 exploited demersal fish species from 1991-2010 to 2041 – 2060 under the SRES A2 scenario (Cheung *et al*., 2011; Cheung *et al*., 2012a). (C) Projected change in the maximum body size of 610 species of marine fishes from 2000 to 2050 under the SRES A2 (between RCP6.0 - 8.5) scenario (Cheung *et al.*, 2012a). The white area is not occupied by the sampled species. (D) Example of projections of maximum fisheries catch potential of 1000 species of exploited fishes and invertebrates from 2000 to 2050 under the SRES A1B scenario (redrawn from Cheung *et al*., 2010).]

Available projections suggest high impacts of ocean warming on coral reefs through coral bleaching, although some of the main assumptions in these approaches need to be verified (CC-CR). Coral reefs are projected to undergo long-term degradation by 2020 to 2100 relative to the 2000s under RCP 3, 4.5 and 8.5 or their equivalent. The degree of impact will depend on their adaptability to thermal stress and the interaction of multiple stressors (Hoegh-Guldberg, 1999; Sheppard, 2003; Donner *et al*., 2005; Meissner *et al*., 2012; Teneva *et al*., 2012; CC-CR). Reefs that are projected to be most threatened by bleaching by 2100 under the SRES A1B scenario, based on different indicators, include the Central and Western Equatorial Pacific, Coral Triangle and parts of Micronesia and Melanesia (Teneva *et al*., 2012). Degradation of coral reefs will impact key ecosystem services (Hoegh-Guldberg, 2011; 6.4; Box CC-CR).

Some groups of marine megafauna are projected to shift in distribution and abundance (6.2.5). Cetacean richness is projected to increase above 40° latitude in both hemispheres and both pinniped and cetacean richness to decrease at lower latitudes by 2040-2049 relative to 1990-1999 under the SRES A1B scenario (Kaschner *et al*., 2011). Using SST as a predictor, the distribution of loggerhead turtles is projected to expand poleward in the Atlantic Ocean and to increase in available habitat in the Mediterranean Sea by 2070-2089 relative to 1970-1989 (Witt *et al*., 2010). Leatherback turtle may decrease in abundance at a rate of 7% per decade because of reduced hatching success with warming following the SRES A2 scenario (Saba *et al*., 2012). Abundance of some seabirds such as Cassin's auklet in the California Current ecosystem or Emperor penguin in Antarctica is projected to decline because of climate induced changes in oceanographic conditions, such as temperature and upwelling intensity (Wolf *et al*., 2010) or summer sea ice conditions (Jenouvrier *et al*., 2012).

6.5.3. Ecosystems and Fisheries

Projected responses of marine ecosystems at different levels of organization are expected to result in large changes in fisheries resources, with increased vulnerability particularly in tropical regions. One of the most direct impacts of climate change on marine ecosystem services is through fisheries (6.4; WGII Ch. 7). Existing projections of impacts on fisheries under climate change are based on changes in ocean net primary production, as well as recruitment, growth, mortality, abundance and distribution of fish stocks. Assuming that the potential fish catch is proportional to net primary production, the fish catch in the North Pacific Ocean subtropical biome is projected to increase by 26% while that in the temperate and equatorial biomes may decrease by 38 and 15%, respectively, by 2100 relative to 2000 under the SRES A2 (RCP6.0 to 8.5) scenario (Polovina *et al*., 2011). Changes in phytoplankton size structure are also projected to affect fisheries catch potential (Cheung *et al*., 2011), resulting in a decrease in the potential catch of large fishes (0 – 75.8%) in the central North Pacific and increases of up to 43% in the California Current region over the 21st century under the SRES A2 scenario (Woodworth-Jefcoats *et al*., 2013). Globally, climate change is projected to result in a large-scale redistribution of global catch potential, with an average 30–70 % increase in yield in high-latitude regions, but a 40 – 60% drop in the tropics by the 2050s relative to the 2000s under

the SRES A1B (RCP6.0) scenario (Figure 6-15) (Cheung *et al.*, 2010; Blanchard *et al*., 2012). This highlights the high vulnerability of national economies of tropical coastal countries through impacts of climate change on fisheries (Allison *et al*., 2009; 6.4). Fisheries targeting specific species may show more complex responses to climate change. For example, driven by changes in temperature and primary production, catches of skipjack and bigeye tuna in the south Pacific were projected to increase by 2035 relative to 1980-2000 under the SRES B1 and A2 scenario, but for 2100, skipjack tuna catch is projected to decrease under the A2 scenario, while bigyeye tuna catch decreases under both A2 and B1 scenarios (Lehodey *et al*., 2011). Regionally, catches in the western Pacific are projected to decrease while those in the eastern Pacific will increase (Lehodey *et al*., 2011). Moreover, driven by changes in growth and distribution under warming and changes in O_2 content, maximum body weight of exploited demersal marine fishes is projected to decrease globally by 10-24% under the SRES A2 (RCP6.0 to 8.5) scenario (Cheung *et al*., 2012a, Figure 6-15). The decrease in maximum body size may affect natural mortality rates, trophic interactions, and reduce yield-per-recruit and, thus, potential catch. Projected changes in the distribution and production potential of fisheries resources are expected to affect economics, human livelihood and food security (Allison *et al*., 2009; Sumaila and Cheung, 2010), although the magnitude and direction of the projected socio-economic impacts are poorly quantified.

Identifying responses to climate change is complicated by species interactions and multiple stressors. OA and hypoxia are expected to reduce maximum catch potential by 2050 relative to 2000 in both the North Atlantic and Northeast Atlantic (Ainsworth *et al*., 2011; Cheung *et al*., 2011). Fishery of molluscs is projected to be particularly vulnerable to OA (Cooley and Doney, 2009), with a substantial decline in the global production of molluscs potentially occurring between 2020 and 2060 (Cooley *et al*., 2012). However, these projections admittedly are sensitive to the assumed vulnerability of the modeled organisms to OA (6.2.5., 6.3.4). Responses of exploited marine species and their fisheries may interact with other human stressors such as overfishing, exacerbating the impacts on fisheries catches (e.g. Lindegren *et al*., 2010; Ainsworth *et al*., 2011). Moreover, differences in vulnerability and adaptive capacity of species to changing environmental and ecosystem conditions will affect the responses of fisheries to climate change (e.g. Fulton, 2011; Griffith *et al.*, 2011; Le Borgne *et al*., 2011). The complex and non-linear interactions and responses of both biophysical and socio-economic systems to climate change and ocean acidification may lead to changes that have a low probability of occurrence based on empirical data (Doak *et al*., 2008). The risk of such low probability but potentially high impact events may be under-estimated in existing model projections (Williams and Jackson, 2007; Lindenmayer *et al*., 2010).

6.5.4. Conclusions

Current understanding is rudimentary of how different modes of forcing like warming, ocean acidification, de-oxygenation and other human impacts, either individually or together, will interact and affect levels of biological organization, from physiology to biomes (i.e., *limited evidence, medium agreement*). Models that integrate climate and ocean changes with biological responses and interactions, and with human activities, at present, have led to some agreement on species and food web responses to climate change. However, these models do not include biological processes such as trophic interactions and evolutionary adaptation that affect responses of biota to physical and chemical changes. Further insights into understanding the relative roles of bottom up and top down effects and their interplay require consideration of scale-dependency, regional and interspecific differences, and improved acquisition and management of biological data. Such insights would improve model projections.

Most projections on ocean biogeochemistry represent open-ocean systems rather well, but coastal and shelf seas regions only poorly. There is a large variation in estimates of the present-day magnitudes and distribution of primary production in models and observation-based estimates (6.1.3., 6.3.1). Accordingly, there is *low confidence* that primary production will decrease by 2100 under low (SRES B1 or RCP4.5) and high emission scenarios (A2 or RCP6.0 - 8.5), also, there is *limited evidence* and *low agreement* and *confidence* on projecting an increase in global NPP or an increase at high latitudes and a decrease in the tropics, although model results are similar.

Confidence is *high* that the distribution of fishes, invertebrates, cetaceans and some marine megafauna will shift further under most emission scenarios, with the projected rates and directions of range shifts being consistent with observations in the last century. More specifically, *confidence* is *high* that the average shift in distribution is

generally poleward at large spatial scales and *confidence* is *medium* in projected shifts of fishes and invertebrates to deeper water, except in areas where hypoxia prohibits deeper movement. Species richness and abundance of warmer-water species will increase at high latitudes (*high confidence*) and decrease in the tropics (*low confidence*). Projections of shifts in abundance and distribution of individual populations and species are more variable and sensitive to model structure and parameters.

Despite some agreement between model results, there is *medium confidence* in the projected direction of fisheries production and *low confidence* in the projected magnitude of changes. Maximum fisheries catch potential is projected to increase at high latitudes and decrease in the tropics by 2050 under SRES B1 (RCP4.5) and A1B (RCP6.0) scenarios (*medium confidence*). *Confidence* in quantifying such projections is *low* due to *low confidence* in projected primary production rates, biological responses such as species interactions, and in projected effects of multiple climate drivers and human activities.

Overall, the projected responses of marine organisms and ecosystems to climate change include changes in primary productivity (*low confidence*), species' life history (*medium confidence*), distribution, abundance and diversity across marine foodwebs (*high confidence*) in a time frame of 20 to 80 years from 2010. These changes increase the vulnerability of human societies, particularly those that are dependent on coastal resources (*limited evidence, medium agreement*) by affecting income, employment and food security through their effects on fisheries, tourism, and regulatory services such as coastal protection (6.4, Box CC-CR, *medium confidence*).

6.6. Chapter Conclusions and Key Uncertainties

This section provides an overview of chapter results on confidence in the detection and projection of climate change effects on ocean systems, as well as in the attribution of effects to the respective forcings (Figure 6-16). Case studies, processes, and concepts relevant in assessing the effects of climate change are represented by their acronyms in text and figure. While the anthropogenic signal is clearly seen in the oceans (6.1.1) clear attribution to anthropogenic influences on climate is not always possible in individual case studies, due to the inherent variability of system characteristics (6.1.3).

[INSERT FIGURE 6-16 HERE
Figure 6-16: Overview of the levels of confidence in detection (left), as well as in projection (right) of climate change effects on ocean systems, in relation to the levels of confidence in attributing these effects to the respective climate forcings. While confidence is often high that there are effects, the direct attribution to one driver in field experiments is difficult as several processes are highly correlated with each other such as warming and changes in stratification and hence nutrient depletion. Some climate change impacts have been condensed into rather broad categories in order not to overpopulate the figures (e.g. **BG**, **B**io-**G**eochemical processes). Note that the term attribution is not only used in the context of detections but also for projections. Projections include both qualitative and quantitative extrapolations and simulations from fundamental principles and models. Experiments (field, laboratory and modeling) simulating future conditions may enhance the respective confidence levels above those for detection which refers to present day observations in the field. The empirical observations resulting from those experiments are directly attributable to the respective drivers. Confidence rises further if these experiments identify the affected mechanisms and their response to future conditions. See text for further discussion of the depicted depicted examples and categories. Confidence assignments focus on the nature and size of effects, not on the capacity of models to reliably quantify their magnitude.]

6.6.1. Drivers of Change and their Effects

Present day observations and those from the **G**eological **R**ecord (**GR**, Figure 6-16) show similar signs in respect to environmental changes, e.g. warm times at high CO_2 levels, and similar ecological consequences in the ocean (*robust evidence, medium agreement* and *confidence*). However, the ongoing rate of anthropogenic CO_2 release and hence ocean acidification is unprecedented in the last 300 Ma (*robust evidence, high agreement and confidence,* 6.1.2).

Long-term observations show **T**emperature **E**ffects (**TE**) through warming-induced species displacements and largely poleward shifts in biogeographical distribution (20 to 200 km per decade) of zooplankton and fishes, paralleled by shifts in seasonal activity, species abundance, migration, and body size (6.3.2., *very high confidence*), and leading to shifts in **C**ommunity **C**omposition (**CC,** *high confidence*). Thermal effects reflect the differential specialization of all life forms on limited ambient temperature ranges. Long-term variability in oceanographic conditions paralleled by observed changes in ecosystem structure and fish stocks also provide *robust evidence* (*high agreement*) for a key role of temperature and changing current regimes in causing these effects. **TE**s are *likely* to continue in the 21st century, causing further changes in **CC** (*high confidence*) and, due to species shifts, decreasing **F**isheries **C**atch **P**otentials (**FCP**) at low to mid and increasing **FCP**s at high latitudes (*high confidence*, 5a in figure). These trends will possibly be strengthened by decreased primary production at low and increased PP at high latitudes but changes in **FCP** due to changes in NPP have *low confidence* (6.5.2., 6.5.3., 6.6.2., 5b in figure). **P**olar **O**rganisms (**PO**) which live at very high latitudes and are unable to migrate, acclimate or adapt to warming (*high confidence*), are becoming marginalized contributing to the projected high species turnover in polar areas (*high confidence*, 6.2.5., 6.5.2).

Hypoxic **Z**ones (**HypZ**), in marine sedimentary habitats and pelagic OMZs presently expand due to restricted water movement (enhanced stratification), warming, elevated microbial respiration, high loading with organic matter and nutrients (*high confidence*). They will continue to expand in the future, due to climate induced warming trends (*high confidence*, 6.1.1., 6.2.3). Vertical expansion of OMZs has led to the compression of habitat for organisms, e.g. pelagic billfishes, with a high O_2 demand (*high confidence*). Overall, there is *medium confidence* that local and regional **H**ypoxia **E**ffects (**HE**) during OMZ expansion are causing habitat loss to groundfishes and pelagic predators and affecting the distribution of key zooplankton and nekton species. Progressive hypoxia is causing shifts in **CC** to hypoxia tolerant species, excluding the calcifiers due to elevated pCO_2 (*high confidence*), benefiting the microbes, and leading to reduced biodiversity and the loss of higher life forms (*robust evidence, high agreement* and *confidence*) (6.2.5., 6.3.3). **HypZ** expansion will cause **HE**s to be exacerbated in the future (*very high confidence*).

Few field observations have detected **O**cean **A**cidification **E**ffects (**OAE**), e.g. through decreases in shell weight of foraminifera (*medium confidence*). Attribution of effects to CO_2 is supported by experimental studies simulating future conditions (*medium confidence*) and showing species-specific sensitivities across phyla (*high confidence*). An acidified surface ocean (due to shifted upwelling and anthropogenic OA) is causing clear negative effects on the oyster aquaculture along the North American west coast (*high confidence* in detection, *low confidence* in attribution to anthropogenic causes), which provides a *high confidence* glimpse into the future of anthropogenic OA and associated **O**yster **E**ffects (**OE**). Projected effects are most harmful in some warm water corals, echinoderms, bivalves, gastropods or crustose algae, and less so in some crustaceans and tropical fishes. Projections from experimental studies and observations at natural analogues indicate shifts in **C**ommunity **C**omposition (**CC**) to more active animals and from calcifiers to non-calcifiers in all organism groups (*high confidence* in both projection and attribution, 6.3.4., 6.2.5).

Climate change involves combinations and synergisms of temperature effects with those of other climate related drivers (ocean acidification, hypoxia, freshening, organism shifts resulting in changing interactions between species, changes in habitat structure, e.g. loss of sea ice). Strong interactions with other human impacts like eutrophication, fishing or other forms of harvesting accelerate and amplify climate induced changes (*high confidence*, 6.2.2., 6.3.5). **S**ynergistic **E**ffects (**SE**) will be exacerbated in the future (*medium confidence*), but have not yet been clearly identified (detected) in the field (*low confidence*). Attribution to such synergisms is supported by experimental evidence, especially in animals or plants (*medium confidence*).

Available evidence from empirical and modeling studies provides *high confidenc*e that climate change impacts marine ecosystems, leading to present changes in provisioning, regulating and supportive **E**cosystem **S**ervices (**ES,** *medium confidence***)**, while there is *limited evidence* and *medium agreement* that climate change affects cultural services. However, attributing their shifts to climate change remains a challenge (*low confidence*), partly because of the intrinsic difficulties of assessing these services, lack of long time-series data and confounding human impacts. However, in light of *high confidence* in projected climate change impacts and available cause and effect

understanding, some services will be affected by future climate change (*high confidence* in projection, *medium confidence* in attribution).

6.6.2. Microbial Responses and Biogeochemical Consequences

Various microbial processes (6.2.3., microbes are archaea, bacteria and protists including phytoplankton) respond to changes in irradiance, nutrient supply, temperature, CO_2 or hypoxia (*high confidence*). Experimental evidence from laboratory and mesocosm studies has identified processes potentially responsive to climate change including impacts of ocean acidification on the N cycle (6.2.3), carbon sequestration and export production, calcification, and respiration with the result of water O_2 depletion and acidification (see **HypZ**). However, the knowledge base is insufficient to build projections on a whole organism understanding of climate impacts on species, strains or communities in the field. A functional **M**icrobial **C**oncept (**MC**) supporting the attribution to climate of detected **M**icrobial **E**ffects (**ME**), from gene to ecosystem to large scale changes in biogeochemistry and also for projections into the future is not available at the current level of understanding (6.3.1., *low confidence*). Overall, *confidence* is *low* in that shifts in **B**io-**G**eochemical processes (**BG**) such as O_2 production, carbon sequestration and export production, nitrogen fixation, climate-feedback by DMS production, nutrient recycling, or calcification are presently happening at detectable scales or will do so in the future, paired with *low confidence* in attribution to climate change (6.3.3., 6.3.4., 6.3.5).

The trends in net primary production (NPP) recently reported for much of the low latitude ocean using satellite observations differ considerably from those few long-term direct estimates of offshore NPP (6.1.3., 6.3.1). The latter indicate a small but significant increase in **g**lobal **NPP** (**gNPP**) over the last two decades (*medium confidence* in detection, *low confidence* in attribution). Higher rates of **NPP** at **h**igh latitudes (**hNPP**, attributable to climate change with *high confidence*, 6.3.1) are indicated by satellite images (*medium confidence*) and may be due to a reduction and thinning of sea-ice. Trends in NPP may be strengthened with further warming. Modeling projects that **gNPP** may decrease by 2100 under SRES A1 and A2 scenarios, however, such global trends cannot presently be quantified with sufficient accuracy and projections are fraught with *low confidence* (6.5.1); for **hNPP**, *confidence* in projections of an increase is equally *low*.

6.6.3. Responses of Animals and Plants and their Implications

Temperature Effects (**TE**) include strong **MA**croorganism **E**ffects (**MAE)**, i.e. effects on animals and plants. Causes and effects are understood for fishes and most invertebrates via their **O**xygen and **C**apacity **L**imited **T**hermal **T**olerance (**OCLTT,** 6.2.2., *robust evidence, medium agreement* and *high confidence*). Such knowledge also supports projections into the future (6.5., *medium confidence*), limited by the unknown potential of organisms to adapt. Alterations in **AB**undance (**AB**) of e.g. corals, fishes or intertidal species result when organisms are exposed to increasing extreme temperatures (*high confidence* in detection and attribution). Such trends will be exacerbated during future warming (*high confidence*, 6.5.2). Multiple drivers (warming, ocean acidification, hypoxia) have **S**ynergistic **E**ffects (**SE**) which can also be understood by analyzing the oxygen and capacity limited thermal tolerance of animals (6.2.6., 6.3.5). The following examples reflect the present predominance of **TE**s. Warming causes shifts in the geographical distribution of North **A**tlantic **C**od (**AC**, 6.3.2., *high confidence* in detection, *medium confidence* in attribution), falling abundance of **E**elpout in the **W**adden **S**ea (**EWS**, 6.2.2., 6.3.2., 6.3.7., *medium confidence* in detection, *high confidence* in attribution), collapsing spawning migrations of **P**acific **S**almon (**PS**, 6.3.2., *high confidence* in detection, *high confidence* in attribution) in the Fraser River, Canada, growth patterns in relation to distribution around New Zealand of **B**anded **M**orwong (**BM**, *high confidence* in detection, *medium confidence* in attribution), and shifts from **S**ardines to **A**nchovies in the Sea of **J**apan (**SAJ**, 6.2.5., 6.3.2., *medium confidence* in detection, *medium confidence* in attribution). Loss of deep habitat and biomass of **M**id-**W**ater **F**ishes (**MWF**, 6.3.3., *medium confidence* in detection) off California is attributed to hypoxia (*high confidence*). At temperate and high latitudes communities display increasing fish **S**pecies **R**ichness (**SR**) resulting from latitudinal shifts of species and loss of sea ice (6.3.7., 6.5.2., *high confidence* in detection, *medium confidence* in attribution). These observed changes have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified. Latitudinal shifts due to **TE**s are projected to

continue in the 21st century under all IPCC emission scenarios (*very high confidence* in detection and in attribution, 6.2.5., 6.3.2., 6.3.5., 6.3.7., 6.4.1., 6.5.2).

Regime shifts and regional changes in **P**lankton **P**henology (**PP**, *medium confidence*) cause changes in food composition and availability to animals, in concert with shifts in their own distribution such as of fishes like **A**tlantic **C**od (**AC**, *medium confidence* in attribution to climate change, 6.3.2). As a consequence, changes in **F**ish **C**atch **P**otential (**FCP**, *high confidence*) due to species shifts and changing species composition (5a in figure) are partly attributable to climate change (*high confidence*) and to maintained fishing pressure (6.5.3).

Among **M**arine **A**ir **B**reathers (**MAB**, i.e. mammals, seabirds and sea turtles), detected effects include changing abundance and phenology, species distribution shifts, and turtle sex ratios (*high confidence*), all of which are attributed to climate change (*high confidence*). These effects are rarely directly linked to climate drivers (e.g. temperature driven turtle sex ratio) but mostly to shifting habitat structure (e.g. loss of sea ice), availability of prey organisms, or foraging efficiency, in both mammals (polar bear, walrusses) and birds (penguins, albatrosses), resulting in differential sensitivities of species. Such trends will be exacerbated by future warming (*high confidence*, 6.2.5).

Increased bleaching and decreased calcification displayed by several **R**eef-building **W**arm water **C**orals (**RWC**, *very high confidence*) over the last three decades are, with *very high confidence*, attributed to the ongoing warming trend and the associated rise in extreme temperature events and amplitudes (6.2.5, Box CC-CR). With *very high confidence*, such trends will be exacerbated during future warming, with some amelioration by latitudinal shifts and evolutionary adaptation (6.3.2., *medium evidence*, *low confidence*). The patterns seen may involve an increasing influence of ocean acidification, confirmed by similar phenomena during mass extinctions in earth history.

6.6.4. Key Uncertainties

Key uncertainties on how the global ocean will respond to climate change, result from the limited number and duration of observational time series in the oceans and thus from insufficient sampling and limited capacity and infrastructure in countries around the world to study ocean response to climate change. Research foci differ between research areas (studies of pelagic versus benthic ecosystems, biogeochemical processes, sensitivities of species, families, phyla or organism kingdoms and domains, and studies of special mechanisms of functioning or adaptation). Processes investigated by various biological disciplines also differ largely between studied organisms, plants, animals, phytoplankton, and bacteria. Each of the listed foci is important but they are usually not well integrated and reductionist with respect to the level of organization in focus, i.e. ecosystem, whole organism, tissue, cell or molecular. Furthermore, scaling from physiological studies on individual species to shifts in species interactions or foodwebs has not been successful to date. A unifying approach addressing principles across organism domains is lacking such that an integrated framework of climate sensitivity at ecosystem level presently does not exist. For all climate drivers, especially ocean warming, acidification and hypoxia, studies integrating mechanistic knowledge and evolution over generations, as well as in various climate zones and biomes are needed. Laboratory and modeling experiments need to be inspired by long-term field observations and observations at natural or paleo-analogues. Modeling activities need to better integrate observations and mechanism-based understanding, last not least in order to better project the future interactions between human and natural systems in a changing climate. As a corollary, the coordination of research concepts and approaches is deficient and a coherent picture of climate change effects is thus not available, leaving a strong coordinating role for international (both inter- and non-governmental) organizations.

Frequently Asked Questions

FAQ 6.1: Why is ocean life fundamental to the planet's sensitivity to climate change?

Oceans cover 70 % of the planet and provide important services to humankind. The life they contain creates about half of the oxygen (O_2) we breathe and also consume by the burning of fossil fuels. Oceans currently absorb ~25 % of the carbon dioxide (CO_2) emitted from the burning of fossil fuels, convert it into organic matter and export parts of it to the deep ocean. Oceans take up 93% of the heat accumulating during global warming and thereby play a key

role in climate regulation. Fisheries and aquaculture provide on average 20 % of the animal protein to more than 1.5 billion people. The oceans provide habitats for charismatic species and sustain ecosystems valued in tourism and for recreation. The rich biodiversity of the oceans offers resources for innovative approaches like medical drug design or biomechanics. Ocean ecosystems contribute to offsetting the effects of natural hazards - for example, coral reefs are known to protect shoreline and efficiently buffer tsunamis and storm surges.

Climate change in the oceans involves rising temperatures, acidification elicited by accumulating CO_2, changed nutrient supply and the expansion of low O_2 areas. These drivers pose risks for ocean life and may impair the ability of marine biota to perform their vitally important functions. Such effects occur on a background of natural variability of these drivers. Additionally, oceans experience other anthropogenic pressures such as overfishing, pollution, nutrient runoff via rivers and the associated eutrophication. In light of the key role of the oceans in global climate change it is crucial but difficult to clearly identify the combined effects of these multiple drivers. Effects of the various drivers may not only be additive but often synergistic, i.e. the effect of each driver is amplified by the concomitant change of the other drivers, causing important but difficult to predict non-linear effects on a wide range of ecosystem processes.

Some insights into future scenarios can be obtained from analysing past events of climate change and from extrapolating the existing long time series (i.e. decades) of data into the future. State-of-the-art ecosystem models built on empirical observations enable us to obtain estimates for responses of marine biota to climate change. Examples are the projected large scale shift in the distribution of commercially relevant fishes to high latitudes and the loss of their catch potential at their original sites. However, formulating well founded or detailed projections is a challenging task because of the large number of interactive feedbacks that must be taken into account. Furthermore, the current rate of environmental change is unprecedented compared to climate changes in the past and, therefore, demands adaptation in only a small number of generations compared to long-term changes in nearly all of the geological record. Changes may thus be too rapid for adaptation to occur. The resilience of marine ecosystems to climate-change mediated impacts is likely to be reduced by the individual and interactive effects of multiple drivers.

FAQ 6.2: What is special about climate change effects on the oceans and can we predict the consequences?

Although there are many similarities in how climate change will alter the land and ocean ecosystems, for example through warming trends, there are also fundamental differences, primarily due to the aquatic environment and associated physicochemical properties of the ocean, including ocean circulation and sea water chemistry. The anthropogenic CO_2 accumulating in the atmosphere enters the ocean and is acidifying the water (making it less alkaline). CO_2 content will thus increase in both the atmosphere and the warming ocean, and be taken up by the organisms. Animals living and breathing in water (for example, fishes, squids, mussels) have naturally 5 to 20 times lower CO_2 levels in their blood and therefore experience stronger changes and are more sensitive than animals on land including aquatic turtles, mammals, seabirds which also live in water but breathe air at the ocean surface.

The warming of the ocean has significant indirect effects on oceanic properties - for example by forming stable ocean layers separated by density differences, which alter the degree of communication between cold nutrient-rich waters at depth and warm nutrient-poor waters near surface. Increasing respiration by organisms in the mid-water layers of stratified oceans will lead to expanding oxygen-poor waters, so-called oxygen minimum zones (OMZs). Respiration also produces CO_2, enriches it further in the water and causes more acidification in expanding OMZs. Low oxygen waters exclude large, more active fishes from living permanently in these areas. Specialized animals with a low O_2 demand will remain such that the communities living in hypoxic areas are very different from those found in well oxygenated waters. Thus, ocean biota (except for sea birds, turtles, mammals) will have to adjust to a fundamentally different environment and one that may be even more altered than that of the land.

At the moment, the uncertainties in modeling prevent any quantification of how much of the change is caused by climate change and how much of it is caused by other human activities. For improved and more reliable projections of future changes, mechanisms and unifying principles shaping the impacts of climate change on various organism groups or on biogeochemical processes must be better understood and included into mechanism based modeling approaches.

FAQ 6.3: How will marine ecosystems look like under climate change?

There is general consensus among scientists that climate change significantly affects marine ecosystems and may have profound impacts on future ocean biodiversity. Recent changes in species distributions, species richness and community structure have been attributed to ocean warming. Projected changes in physical and biogeochemical drivers, such as warming, acidification, hypoxia, nutrient supply and sea ice cover, will continue to affect marine

biota. Under most climate change scenarios, a shift or expansion of habitat range limits towards higher latitudes by tens of kilometres per decade can be foreseen for many species of plankton, fishes and invertebrates, resulting in shifts of species richness and altered community composition. Organisms that are more tolerant to direct effects of climate change may be affected indirectly through climate change restructuring existing food webs. In polar areas cold-adapted species among invertebrates and fishes may be lost by local extinctions and be marginalized due to warming. Similarly, species in semi-enclosed seas such as the Wadden Sea and the Mediterranean Sea face higher risk of local extinction because distributional shifts in response to warming and other environmental changes are limited by the land-boundary.

Overall, climate change will lead to large-scale shifts in the patterns of marine productivity, biodiversity, community composition and ecosystem structure. Extinction of species that are sensitive to climate change, including ocean acidification, will lead to a decrease in species richness. In particular, the impacts of climate change on vulnerable organisms such as warm water corals are expected to affect the associated ecosystems, such as coral reefs. Alteration of the seasonal activity (phenology) of marine organisms, their biology and distribution will disturb food web interactions such as the grazing of copepods (small crustaceans) on planktonic algae. Ocean primary production is also expected to change but the global patterns are more difficult to project. Existing model projections suggest an increase in primary production at high latitudes such as in the Southern Ocean (higher mean light levels for photosynthesis at lower ice cover) and decreases in the tropics and at mid-latitudes (reduced nutrient supply). Human stressors such as overfishing, eutrophication and pollution are expected to exacerbate the impacts of climate change. Increasing temperature, nutrient fluctuations, and eutrophication may favor harmful algal blooms in coastal including upwelling areas. Climate change may also cause shifts in the distribution and abundance of pathogens such as for cholera.

FAQ 6.4: Why do marine organisms rely on a sufficiently alkaline ocean?

Many marine species, ranging from microscopic plankton to shellfish and coral reef builders are generically referred to as calcifiers, as they depend on using solid calcium carbonate ($CaCO_3$) to construct their skeletons or shells. Solid calcium carbonate comes in different forms called calcite and aragonite; aragonite is more soluble in water than calcite. Sea water contains ample calcium in solution but this needs to be transported to the sites where calcification occurs. In contrast, the carbonate is not transported from the water to calcification sites but newly formed where it is needed. To form carbonate ions in high concentrations and to thereby calcify more easily, the calcification site is made alkaline, meaning that pH is increased by the organism to values higher than in other parts of the body or in ambient sea water. This process demands energy which the organism has to be able to supply. If high CO_2 levels from outside penetrate the organisms this process is becoming even more challenging and costly. If a lot of energy is needed for calcification, energy for other biological processes like growth might become limiting, making these organisms less competitive, reducing their weight or reproduction, all of which is needed for sustaining ecosystem diversity, and services.

CO_2 accumulating in the seawater can also affect the stability of shells and skeletons (Box CC-OA). At low CO_2 levels, the sea water has high carbonate levels and keeps $CaCO_3$ in solid form. As the oceans acidify, by the anthropogenic accumulation of CO_2, the concentration of carbonate falls making $CaCO_3$ more soluble and this water may start dissolving carbonate shells. Some of these shells are shielded from direct contact with sea water by a special coating (as is the case in mussels). Combined with the increased energy needed for calcification, organisms might struggle to repair their shells which are dissolving in corrosive seawater. Presently, corrosive waters upwelling closer to the Northwest coast of the United States impact the oyster aquacultures and illustrate the principles of such effects.

Ocean acidification not only affects species producing calcified exoskeletons. Ocean acidification affects organisms either directly or indirectly. For most organisms investigated, sensitivity is highest at extreme temperatures and thus, at the edges of their thermal ranges highlighting the potential for combined effects with temperature. Indirect effects might be changes in their prey organisms due to their specific sensitivities to climate change. Ocean acidification therefore has the potential to disturb food webs and fisheries.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

[Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building (scleractinian) corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics. About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and are likely to derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including those from provisioning (food, construction material, medicine), regulating (shoreline protection, water quality), supporting services (oxygen supply) and cultural (religion, tourism). This is especially true in small islands (29.3.3.1).

Most human-induced disturbances to coral reefs were local (e.g., coastal development, pollution, nutrient enrichment and overfishing) until the early 1980s when global and climate-related disturbances (ocean warming and acidification) began to occur. Temperature and seawater acidity are two of the most important environmental variables determining the distribution of coral reefs (Kleypas et al., 2001). As corals are centrally important as ecosystem engineers (Wild et al., 2011), the impacts on corals have led to widespread degradation of coral reefs.

A wide range of climatic and non-climatic stressors affect corals and coral reefs and negative impacts are already observed (5.4.2.4, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae (genus *Symbiodinium*), which live in the coral tissues and play a key role in supplying the coral host with energy and nutrients (Baker et al., 2008) (see 6.2.5 for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies, is the most widespread and conspicuous impact (Fig. 5X; see Sections, 5.4.2.4, 6.2.5, 25.6.2, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Elevated temperature along with ocean acidification reduces the calcification rate of corals (*high confidence*; 5.4.2.4), and may tip the calcium carbonate balance of reef frameworks towards dissolution (*medium evidence and agreement*; 5.4.2.4). These changes will erode fish habitats with cascading effects reaching fish community structure and associated fisheries (*robust evidence, high agreement*, 30.5).

Around 50% of all coral reefs have experienced medium-high to very high impact of human activities (30-50% to 50-70% degraded; Halpern et al., 2008), which has been a significant stressor for over 50 years in many cases. As a result, the abundance of reef building corals is in rapid decline (1 to 2% per year, 1997-2003) in many Pacific and SE Asian regions (Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and coral bleaching have led to a decline in coral cover on the Great Barrier Reef (about 51% between 1985 and 2012; De'ath et al., 2012).

One third of all coral species exhibit a high risk of extinction, based on recent patterns of decline and other factors such as reproductive strategy (Carpenter et al., 2008). Although less well documented, non-coral benthic invertebrates are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation coral reefs, including in a marine reserve (Jones et al., 2004). While many factors, such as overfishing and local pollution, are involved in the decline of coral reefs, climate change through its pervasive influence on sea temperature, ocean acidity, and storm strength plays a very significant role.

There is *robust evidence* and *high agreement* that coral reefs are one of the most vulnerable marine ecosystems (Chapters 5, 6, 25, and 30). Globally, more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011) even in the absence of climatic factors. Future impacts of climate stressors (ocean warming, acidification and sea level rise) will exacerbate the impacts of non-climatic stressors (*high agreement, robust evidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9–60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation under the RCP3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30–88%, 68% uncertainty range). If present day corals have residual capacity to acclimatize and/or

adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan et al., sbm). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia & Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton et al. (2012) are already exploiting their coral reef fisheries in an unsustainable way (13.X.X).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4, 30.5).

Coral reefs make a modest contribution to the global domestic product but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent on average 5% of the GDP of South Pacific islands (Laurans et al., 2013). At the local scale, these two services provide at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are less effective in reducing coral loss from thermal stress (Selig et al., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012). Controlling the input of nutrients and sediment from land is an important complementary management strategy because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2012). There is also high confidence that, in the long term, limiting the amount of warming and acidity is central to ensuring the viability of coral reef systems and dependent communities (5.X.X and 30.5).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction

Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult; observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and

ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to

calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

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Table 6-1: Selected examples of long-term biological and ecological observations in the oceans (NPP denotes Net Primary Productivity).

Region	Name of time series	Duration covered	Type of information	Interpretation
Global	SeaWiFS (Sea-viewing Wide Field-of-view Sensor)	1997-2011	Near surface chlorophyll	Direct and indirect effects of warmer oceanic conditions, associated with climate variability, result in lower chlorophyll concentrations and decreased rates of NPP (Behrenfeld *et al.* 2006a). Satellite time-series is insufficient to make robsut projections on the effect of climate change on chlorophyll concentrations or rates of NPP (Henson *et al*., 2010)
English Channel and later into the open sea	CPR (Continuous Plankton Recorder)	1920s - ongoing	Zoo- and phytoplankton abundance/ presence absence	• changes in the seasonal abundance of phytoplankton (Edwards *et al.*, 2001) • rapid northerly movements of temperate and subtropical species of zooplankton and phytoplankton (Beaugrand *et al.*, 2009) • climate induced trophic mismatch between phytoplankton and zooplankton and its impact on fisheries (6.3.2.; Edwards and Richardson, 2004)
North Sea	Helgoland Roads (Alfred Wegener Institute)	1962 - ongoing	salinity, secchi disk depth, macronutrients, phytoplankton, zooplankton, intertidal macroalgae, zoobenthos and bacterioplankton	• Increase in green algae, decrease in brown algae, increased number of invaders on macrofauna, changing foodweb and bloom dynamics (Wiltshire *et al.*, 2010)
California	CalCOFI (California Cooperative Oceanic Fisheries Investiga-tions)	1949 - ongoing (quarterly, 1969-1984 triennial) on variable grid	Ecological assessment	• El Niño impacts marine invertebrates and fishes (Chelton *et al*., 1982; Butler, 1989; Rebstock, 2001) • decline in zooplankton biomass during periods of warming (Roemmich, 1992; Roemmich and McGowan, 1995a; Roemmich and McGowan, 1995b) • multidecadal shifts in the pelagic ecosystems (sardines and anchovies) (Brinton and Townsend, 2003; Lavaniegos and Ohman, 2003; Chavez *et al*., 2003).
North Pacific Subtropical gyre	Climax HOT (Hawaii Ocean Time-series)	1968 - 1985 and 18 expeditions, mostly in summer months 1988 - ongoing monthly	ecosystem structure and variability	• Doubling of ship-measured chlorophyll a concentrations during period 1968-1985 (Venrick *et al*., 1987). • Change from large eukaryotic to small photosynthetic prokaryotes (Karl *et al*., 2001) • Decrease in dissolved phosphate concentrations due to proliferation of nitrogen fixing microorganisms (Karl 2007b)

Fisheries data series	Various	Various, see to the right	Fish stock assessments	• from 1950, fisheries landings and aquaculture production statistics, FAO: http://www.fao.org/fishery/statistics/en • from 1950, Sea Around Us project: www.seaaroundus.org, • from 1950, Global fishing effort database, Anticamara *et al*., 2011; • from 1970, ICES Trawl Surveys – DATRAS, ICES: http://datras.ices.dk/Home; • from 1950, RAM Legacy Stock Assessment Database (Ricard *et al*., 2012) • from 1903, British landings and effort data for major exploited fish stocks (Engelhard, 2005, ICES, 2010, 2011)

Table 6-2: Variations in metabolism based on sources of energy, electrons and carbon according to Karl (2007a), complemented by the taxa which exploit these pathways. Mode of metabolism may relate to organizational complexity and tolerance to environmental extremes (Figure 6-8).

Source of Energy[1]	**Source of Electrons**	**Source of Carbon**	**Domain / Taxon**
Sunlight *photo-*	Inorganic *-litho-*	CO_2 *-autotroph*	Bacteria, Archaea, Eukarya (algae and higher plants)
	Organic *-organo-*	Organic *-heterotroph*	Bacteria
Chemical *chemo-*	Inorganic *-litho-*	CO_2 *-autotroph*	Bacteria Archaea
	Organic *-organo-*	Organic *-heterotroph*	Bacteria Archaea Eukarya (Protozoa, Metazoa)

[1]A "mixotroph" is an organism that has the ability to use more than one source of energy, electrons or carbon

Table 6-3: Environmental forcing on biological production by physical, chemical and biological characteristics of major pelagic ecosystems (Adapted from Barber, 2001, based on the original analysis by McGowan, 1974).

	Size		**Stratification**			**Nutrient**[1]	
System	**Area (km^2x10^6)**	**%**	**Degree of**	**Duration**	**Productivity and Pattern**	**Level**	**Source**
Low-latitude gyre	164	52	Strong	Permanent	Low to to medium (debated)	Low	Eddy diffusion
Southern Ocean	77	25	Very weak, except strong when ice melts in summer	Seasonal	Moderate to high in summer only, Strongly seasonal	High	Mixing and upwelling
Equatorial upwelling	22	7	Aperiodic, upward vertical transport (temporally variable ranging from active upwelling to permanent stratification)	Permanent	High, Continuous	High	Upwelling and horizontal mixing
Subarctic gyre	22	7	Moderate stratification following winter mixing	Seasonal convective mixing	Low in winter, Strongly seasonal	High	Convective mixing and eddies
Eastern Boundary Current	21	7	Medium	Permanent	Moderate, Seasonal	Medium	Upwelling and lateral advection
Coastal upwelling	6	2	Strong stratification following vertical transport	Continuous	High, Weakly seasonal	High	Upwelling

[1]Nitrate and phosphate

Table 6-4: A wide range of processes make up the ocean's biological pump (Figure 6-6). In order to assess how a changing climate will alter the functioning of the pump, and the resulting biogeochemical feedbacks on global climate, the cumulative effects of climate-change mediated alteration of processes from cellular to ocean basin, and from pelagic to mesopelagic, must be quantified. This table illustrates, using published information, the complexity of the integrated knowledge platform needed to provide evidence of these biogeochemical ramifications and thus the limits to clear conclusions about climate induced effects on the biological pump (C, Carbon; TEP, Transparent Exopolymer Particle; DOM, Dissolved Organic Matter; POM, Particulate Organic Matter).

Alteration of physiological rates	Biogeographical changes	Altered foodweb structure - Trophodynamics	Changes to particle dynamics	Biogeochemical changes / climatic feedbacks
NPP (Bopp *et al*., 2002)	Microbial community structure (Giovannoni and Vergin, 2012)	Altered prey-predator linkages (Lewandowska,and Sommer, 2010)	Faecal pellet geometry (Wilson *et al*., 2008)	Particle flux/C sequestration (Bopp *et al*., 2002)
Bacterial ectoenzymes (Christian and Karl, 1995)	Phytoplankton community structure – biomes (Boyd and Doney, 2002)		C partitioning between DOM vs. POM – TEP (Riebesell *et al*., 2007)	Shifts in elemental stoichiometry of planktonic communities (Karl *et al*., 2003)
TEP production (Engel *et al*., 2004)	Alteration of zooplankton biomes (Beaugrand *et al.*, 2009)		Sinking rates/seawater viscosity (Lam and Bishop, 2008)	Remineralization rate – [O_2]; hypoxia; nutrient resupply (Gruber, 2011)
Microzooplankton grazing rates (Rose *et al*., 2009)			Ballasting - calcite versus opal (Klaas and Archer, 2002)	Activity of the microbial loop; vertical carbon export (Grossart *et al.*, 2006; Piontek *et al*., 2010)

Table 6-5: Assessment of effects of ocean acidification on marine taxa with the number of laboratory and field studies, processes, parameters and total number of species studied in the range from pCO_2 <650 to >10000 µatm. Processes and parameters investigated in multiple life stages include growth, survival, calcification, metabolic rate, immune response, development, abundance, behaviour and others. Not all life stages, not all parameters and not the entire range of CO_2 concentrations were studied in all species. *Confidence* is based on the number of studies, the number of species studied and the agreement of results within one group. E.g. most species of calcifying macroalgae were negatively affected when exposed to a pCO_2 of 670 µatm (RCP 6.0 in 2100), considering e.g. calcification or growth, which renders the group as vulnerable with *medium confidence*. +: denotes that possibly more species or strains were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: most species were negatively affected; tolerant: most species were not affected. RCP 6.0: representative concentration pathway with projected atmospheric pCO_2 = 670 µatm in 2100; RCP 8.5: representative concentration pathway with projected atmospheric pCO_2 = 936 µatm in 2100 (Meinshausen *et al.*, 2011). *Confidence* is limited by the short to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary timescales, across generations (see separate reference list). For an assessment of variability between species from the same phylum see Figure 6-10.

Taxon	No. of studies	No. of para-meters studied	Total no. of species studied	pCO_2 where the most vulnerable species is negatively affected or investigated pCO_2 range* (µatm)	Assessment of tolerance to RCP 6.0 (*confidence*)	Assessment of tolerance to RCP 8.5 (*confidence*)
Cyanobacteria	8	5	5+	370-1000*	Beneficial (*low*)	Beneficial (*low*)
Coccolithophores	20	6	4+	800	Tolerant (*low*)	Vulnerable (*low*)
Diatoms	9	5	7+	400-820*	Tolerant (*low*)	Tolerant (*low*)
Dinoflagellates	5	4	3+	350-750*	Beneficial (*low*)	Beneficial (*low*)
Foraminifers	7	4	5	800	Tolerant (*low*)	Vulnerable (*low*)
Seagrasses	3	6	4	300-21000*	Beneficial (*medium*)	Beneficial (*medium*)
Macroalgae (non-calcifying)	5	5	3+	350-20812*	Beneficial (*medium)*	Beneficial (*low*)
Macroalgae (calcifying)	15	10	19+	550	Vulnerable (*medium*)	Vulnerable (*medium*)
Corals	25	17	22+	560	Tolerant (*low*)	Tolerant (*medium*)
Annelids	4	6	4+	2800	Tolerant (*medium*)	Tolerant (*medium*)
Echinoderms	33	29	29+	600	Tolerant (*medium*)	Vulnerable (*high*)
Molluscs	54	33	40+	600	Vulnerable (*low*)	Vulnerable (*high*)
Bryozoans	2	3	5+	2900	Tolerant (*medium*)	Tolerant (*medium*)
Crustaceans	33	27	37	700	Tolerant (*low*)	Tolerant (*medium*)
Fish	30	24	25	700	Vulnerable (*low*)	Vulnerable (*low*)

Table 6-6: Selected ocean acidification effects on microbes and associated processes. The experiments were conducted throughout more than a decade which large changes in experimental setup and data reporting (Riebesell *et al*., 2010) though information is still underreported in more recent papers, e.g. Krause *et al*, 2012, report pH values but not CO_2 or other carbonate system parameters. Therefore, pH as a common variable is reported in this table and not CO_2. The CO_2 values range from 150ppm (in this example pH 8.52) to 1500 ppm (pH 7.69) but changes in dissolved inorganic carbon (DIC) and total alkalinity (TA) do not allow a direct conversion from CO_2 to pH. Also note that the pH scale used was not always reported which can lead to errors up to 0.15 pH units between the NBS and free scale.

Organism	pH	Effect	Synergistic effects	reference
Archaea and ammonium oxidizing **bacteria**	pH reductions by 0.05–0.14 in water samples from various field sites	Decreased nitrification rates		Beman *et al.*, 2011
Batch bacterial community	8.22-8.15, 7.82, 7.67	Community shift No change in abundance		Krause *et al*., 2012
Cyanobacteria	8.4, 7.8	Prochlorococcus/ Synechococcus – no clear change in C-fixation Trichodesmisum – enhanced rates of N_2 and C fixation	With excess Fe, P	Lomas *et al*., 2012
Trichodesmium	8.52 to 7.69	Enhanced rates of photosynthesis, higher cell division rates, altered nutrient utilization (C:N and C:P ratios) and enhanced rates of N_2 fixation	Under P limitation	Barcelos e Ramos *et al.*, 2007; Hutchins *et al.*, 2007; Kranz *et al.*, 2010
Trichodesmium	8.35-7.80	Decreased N_2 fixation rates and growth	under iron limitation	Shi *et al.*, 2012
Trichodesmium erythraeum	8.28-8.01	No increase in N_2 fixation No increase in CO2 fixation	High light Low light	Garcia *et al.*, 2011
Synechococcus	8.05, 7.80	Increased cell division higher photosynthetic rate	Ambient temperature versus 4°C warming	Fu *et al.*, 2007
Prochlorococcus	8.05, 7.80	No change	Ambient temperature versus 4°C warming	Fu *et al.*, 2007
Diatom				
Pseudo-nitzschia fraudulenta	8.4, 8.2, 7.9	Increased toxicity Higher growth rate	Si limitation	Tatters *et al.*, 2012
Pseudo-nitzschia multiseries	8.38, 7.94	Increased toxicity		Sun *et al.*, 2011
Diatom-dominated assemblages		Increased primary production		Tortell *et al.*, 2008
Thalassiosira weissflogii	8.10, 7.8			Shi *et al.*, 2009

Coccolithophores				
Emiliania huxleyi	Various levels	Increased growth		Riebesell *et al.*, 2000; Rost *et al.*, 2003; Leonardos and Geider, 2005
Dinoflagellates				
Prorocentrum minimum	8.28 to 8.01 (based on T, DIC, CO_2)	Higher carbon fixation rates growth unaffected		Fu *et al.*, 2008

		CALCIFICATION	
Species	pH	Effect	Reference
Emiliania huxleyi	8.2-7.75 ~8.5-~7.9	Reduced calcite production Increased POC production reduced PIC/POC	Riebesell *et al.*, 2000; Zondervan *et al.*, 2001; For list see Ridgwell *et al.*, 2009 and Hoppe *et al.*, 2011
Emiliania huxleyi Strain NZEH	8.15, 8.13, 7.96, 7.85, 7.77	Increased PIC production by 80% Increased POC by 150% No change in PIC/POC	Iglesias-Rodriguez *et al.*, 2008
Emiliania huxleyi Strain RCC1256 Strain NZEH	Numerous experiments 8.44 - 7.2	No change in POC production 10% Reduced calcification between 288 to 1206 µatm, lower growth No change in growth, slightly reduced calcification and POC	Hoppe *et al.*, 2011;
Emiliania huxleyi Strain NZEH	8.10, 7.8	36% increase in PIC 69% increase in POC	Shi *et al.*, 2009
Emiliania huxleyi	Various experiments from 8.45 to 7.77	35% reduction in calcification between 200 and 900 µatm No change in POC Optimum response in POC	Langer *et al.*, 2009
Emiliania huxleyi		Independent of light limitation reduction in PIC/POC, POC independent of light PIC decrease with increasing CO2 at high light, Unaffected at low light	Zondervan *et al.*, 2002
Emiliania huxleyi	8.02, 7.82	Under nitrogen limitation: reduced calcite production and reduced POC, smaller cell volume	Sciandra *et al.*, 2003
Emiliania huxleyi mescosm		40% decrease in net community calcification from 175 to 600 ppmV CO_2 no change in NPP Calcite formation decreased with CO_2 concentration, reduction of weight of liths, Increased TEP formation from 190, 410 to 710 ppmV CO_2	Delille *et al.*, 2005; Engel *et al.*, 2005
Calcidiscus leptoporus	8.74, 8.44, 8.27, 8.13, 7.93, 7.86 8.33, 8.34, 7.72, 7.6, 7.49, 7.86	Optimum calcification at 400ppm Optimum calcification between 400-900 ppm various methods in altering carbonate chemistry	Langer *et al.*, 2006 Langer *et al.*, 2011
Coccolithus pelagicus	8.56, 8.22, 7.81	No significant change	Langer *et al.*, 2006
Gephyrocapsa oceanica	8.2-7.75	Reduced calcite production, reduced PIC/POC	Riebesell *et al.*, 2000; Zondervan *et al.*, 2001

Table 6-7: Examples illustrating species vulnerabilities and underlying mechanisms to changing temperature, hypoxia, ocean acidification (OA).

General pattern	Phenomenon	Driver	Mechanism / Sensitivity	References
Species displacement, regime shifts abundance losses	Northward shift in the distribution of North Sea cod (*Gadus morhua*) stocks	Winter/spring warming (*high confidence*)	Bottlenecks of high sensitivity during early life stages as well as adult spawning stage in winter/early spring	Perry *et al.*, 2005; Pörtner *et al.*, 2008
	Decreased abundance of northern temperate species, increased abundance of southern species in the Bay of Biscay (France)	Increasing annual mean temperatures at 100 m depth.	Bottlenecks of high sensitivity during recruitment	Hermant *et al.*, 2010
	Shift from sardines (*Sardinops melanostictus*) to anchovies (*Engraulis japonicus*) in the Sea of Japan observed between 1993 and 2003	Warming (*high confidence*) at the interdecadal scale	Thermal windows of growth and reproductive output are found at higher temperatures for anchovies than sardines, food preferences of the competing species being similar.	Li *et al.*, 1992; Takasuka *et al.*, 2007, 2008
	Bigeye (*Thunnus obesus*), skipjack (*Katsuwonus pelamis*), albacore (*T. alalunga*), yellowfin (*Thunnus albacares*) or bluefin tuna (*T. maccoyli*), mildly affected by warming trends, shifting core habitat, abundances, and heat stress of spawners projected.	Wide specific thermal ranges (Bigeye 11-29, skipjack 17-30, yellowfin 18-31 or bluefin tuna 10.5-21, albacore 13-25°C; optimal thermal window narrowest and warmest during spawning, effects of reduced primary productivity.	– Eurythermal tissue characteristics, large body size, wide roaming ranges. – Larvae most sensitive to water temperature, widening their thermal habitat as they grow. – Adults at spawning stage need to prevent overheating, a shift in location to cooler waters may occur to maintain spawning success, e.g. in surface-dwelling skipjack tuna.	Katz, 2002; Pörtner, 2004; Lehodey *et al.*, 2011; Hazen *et al.*, 2012
	Variable sensitivity of Pacific tuna species to the availability of dissolved O_2. Bigeye tuna routinely reach depths where ambient O_2 content is below 1.5 ml L^{-1} (≈ 60 µmoles kg^{-1}).	Species specific exposures and tolerances to hypoxia, related to feeding activity in hypoxic zones.	Oxygen transport via hemoglobin is adapted to be highly efficient supporting high metabolic rates as needed during feeding in the OMZ.	Lehodey *et al.*, 2011; Seibel, 2011
	Variable sensitivities to OA within and across animal phyla (Figure 6-9 B)	Anthropogenic OA, Sea water acidification by elevated pCO_2 in OMZs, upwelling areas, involving	– Lowered extracellular (blood plasma) pH causing a lowering of the rates of ion exchange and metabolism in muscle	Reipschläger and Pörtner, 1996; Pörtner *et al.*, 2000; Vezzoli *et al.*, 2004; Langenbuch and Pörtner, 2003;

		anthropogenic ocean acidification.	or liver (hepatocytes) of vertebrates and invertebrates. – High sensitivity at reduced energy turnover in tissues and/or whole organism by – reduced ion exchange, – use of more energy efficient transport mechanisms, – reduced protein synthesis, enhanced nitrogen release from amino acid catabolism and protein degradation, – slower growth	Fernández-Reiriz *et al.*, 2011; Langenbuch and Pörtner, 2002; Langenbuch *et al.*, 2006; Michaelidis *et al.*, 2005; Pörtner *et al.*, 1998; Stumpp *et al.*, 2012
			Further affected fitness-relevant processes: – gonad maturation, – egg fertilization, – egg haching, – brooding success, – larval development, – critical transition phases in development (onset of feeding, moulting), – larval and adult calcification and growth, – neuronal metabolism and functioning, behaviors (feeding, disorientation and distortions in olfactory and acoustic perceptions) – immune response, – exercise performance	Bibby *et al.*, 2008; Boyd and Burnett, 1999; Chan *et al.*, 2011; Dupont *et al.*, 2008; Kurihara and Shirayama, 2004; Kurihara, 2008; Havenhand *et al.*, 2008; Hernroth *et al.*, 2011; Kawaguchi *et al.*, 2011; Michaelidis *et al.*, 2005; Munday *et al.*, 2009c, 2010; Nilsson *et al.*, 2012; Pörtner, 2002b; Reuter *et al.*, 2011; Reipschläger *et al.*, 1997; Sewell and Hofmann, 2011; Shirayama and Thornton, 2005; Simpson *et al.*, 2011; Walther *et al.*, 2010.

Table 6-8: Examples of observed biological responses resulting from temperature and temperature-mediated changes in the ocean.

Responses and attribution	References
Species abundance, biogeography and diversity	
Observations by the European Large Marine Ecosystems study report the northward movement of species and the conversion of polar into more temperate and temperate into more subtropical system characteristics. Effects are attributed to climate change but may be influenced by nutrient enrichment and overfishing. Due to the lack of geographical barriers and to advective processes, the mean poleward movement of plankton reached up to 200–250 km per decade between 1958–2005.	Beaugrand *et al.*, 2009; Philippart *et al.*, 2011
Retreat of colder water plankton to the north in the Northeast Atlantic between the 1950s and 2000s.	Beaugrand *et al.*, 2002
Between 1960 and 2000 the Newfoundland Shelf in the Northwest Atlantic saw an increase in the abundance of arctic boreal plankton species, notably the copepods *Calanus hyperboreus* (Kroyer), *Calanus glacialis* (Jaschnov) and the dinoflagellate *Ceratium arcticum* due to an increased contribution of Arctic water via the shelf branch of the Labrador Current. In 1996, a dramatic drop in the NAO allowed a flood of cool Labrador slope water to round the tail of the Grand Bank, carrying *C. hyperboreus* along the Scotian shelf-break, to reach Georges Bank two years later.	Johns *et al.*, 2001; Greene and Pershing, 2003
In the Southwest Atlantic sector and the Bellingshausen Sea a historical analysis of the distribution of Antarctic macrozooplankton between 1925 and 1951 demonstrated the key role of temperature and differential thermal windows in setting distribution ranges. Food (chlorophyll *a*) availability codefined the distribution of krill (*Euphausia superba*).	Mackey *et al.*, 2012
NAO-driven variability in growth rate has been documented for the Atlantic quahog, *Arctica islandica* from Iceland, the coralline alga *Clathromorphum compactum* off Newfoundland and the bivalve *Clinocardium ciliatum* in the Barents Sea (combined NAO and ACRI). A role for temperature has yet to be unequivocally demonstrated.	Schöne *et al.*, 2005; Carroll *et al*., 2011; Halfar *et al.* 2011
A benthic fish species, the eelpout (*Zoarces viviparus*) at its southern distribution limit, the German Wadden Sea, displayed abundance losses during warming periods and rising summer extreme temperatures, with early disappearance of the largest individuals.	Pörtner and Knust, 2007
Studies of tropical coral reefs document large scale bleaching (6.2.2.4.4.), growth reductions and decreased calcification in *Porites* and other corals over the last two decades, a change unprecedented in the last centuries largely induced by warming.	Lough, 2008; De'ath *et al.*, 2009; Cooper *et al*., 2012
The giant kelp *Macrocystis pyrifera* off the eastern north Pacific has shown changes in both distribution and abundance during major El Niño events (Tegner and Dayton, 1987; Tegner et al., 1996), with particularly strong consequences and widespread mortality at its southernmost distribution limit off Baja California.	Ladah *et al*., 1999; Valdez *et al*., 2003
In the Northwest Atlantic the majority of fish caught in trawl surveys show a northward movement in response to warming since the 1960s, with some of the shifts being correlated with the AMO.	Nye *et al*., 2009; Lucey and Nye, 2010; Nye *et al*., 2011

Responses and attribution	References
Phenology	
In the waters around the U.K., during a period of warming between 1976 and 2005, the seasonal timing of biological events of all major marine taxonomic groups (plant/phytoplankton, invertebrate and vertebrates) advanced on average, by 0.31 to 0.43 days year^{-1}	Thackeray *et al*., 2010.
Migration time of pink salmon (*Oncorhynchus gorbuscha*) in Alaska is almost two weeks earlier now relative to 40 years ago which is related to warming. This is related to the rapid microevolution for earlier migration timing.	Kovach *et al*., 2012
Body size	
Asymptotic size of different populations of Atlantic cod (*Gadus morhua*) and Atlantic Herring (*Clupea harengus*) are negatively related to temperature.	Taylor, 1958, Brunel and Dickey-Collas, 2010
Decrease in asymptotic size of haddock (*Melanogrammus aeglefinus*) in the North Sea from the 1970s to the 2000s is significantly related to changes in sea surface temperature.	Baudron *et al*., 2011
Trophic and competitive interactions	
Both warming and the decreasing spatial extension of krill habitat benefits the salp (Pakhomov, 2004) and may also govern the on-going reductions in Adelie and chinstrap penguin populations via reductions in prey availability.	Trivelpiece *et al.*, 2011.
Direct effects of warming on both, the Atlantic cod and the putative copepod prey species of juvenile cod are involved in climate effects on Atlantic cod (*Gadus morhua*) populations in the Eastern North Atlantic. The regime shift in the North Sea, from the larger copepod *Calanus finmarchicus* to ones forming lower biomass including *C. helgolandicus* represent an unfavorable shift to less energy dense food particles for juvenile cod and to a later timing for reproduction, such that *Calanus* eggs and nauplii are less abundant as food for newly hatched cod larvae. This shift was thereafter shown to be largely caused by temperature.	Beaugrand *et al*., 2003; Helaouët and Beaugrand, 2007
Significant community-wide changes in abundance and composition among 150 intertidal and subtidal algae and invertebrates resulted from direct effects of temperature on key taxa as well as indirect effects through ecological interactions after long-term warming by 3.5 °C from 1985 to 1995 at a power station in temperate California. In the Californian intertidal after warming by 0.79-1.26 °C within 60 years (1931-1933 vs. 1993 -1996) southern species increased and northern decreased in abundance, in line with range-related community shifts.	Sagarin *et al.*, 1999
The relative ranges of predator (sea stars) and prey (mussels and barnacles) change in response to climatic differences reflecting and leading to associated changes in interactions and modifications in predator pressure.	Harley, 2011
In tropical seas, turf algae can rapidly colonize thermally damaged corals depending on the extent to which coralline red algae, which are the most important substrate for coral recruitment, suffer from ocean acidification.	Doropoulos and Diaz-Pulido, 2013; Fricke *et al*., 2011; Hoegh-Guldberg *et al*., 2007

Table 6-9: Potential interactions between modes of anthropogenic forcing (environmental; harvesting; or complex; considering scales and velocity of change, frequency and variability of events, intensity) on different levels of biological organisation. These interactions, from simple to complex, are illustrated with published illustrative examples ranging from physiological studies (Pörtner and Knust, 2007) to modelling studies such as Griffith *et al.*, (2011). E, O, and M denote studies using manipulation Experiments (lab or field), Observations, or Modelling approaches, respectively; note there are an insufficient number of studies to assign a level of confidence to each of these findings "???" defines the bounds on our understanding of the relationship between forcing and its effect on organisational level.]

Anthropogenic Forcing

Biological Organisation studied at ecosystem level	*Single Environmental Driver*	*Multiple Environmental Drivers*	*Fishing / Foodwebs*	*Fishing / Climate change*
Individual species	Lab experiments and field observations show that warming alters organismal physiology and thereby, in situ abundance (Pörtner and Knust, 2007) E & O	Shipboard manipulation experiment addressing interactive effects of temperature and CO_2 on coccolithophore calcification (Feng *et al.*, 2009) E	Interactive effects of multiple drivers on larval fish (Perry *et al.*, 2010; Runge *et al.*, 2010) O & M	???
Population	Lab cultures show how altered pH elicits different responses of coccolithophore species (Langer *et al.*, 2006) E	Lab cultures show differential responses of cyanobacterial groups to temperature and CO_2 (Fu *et al.*, 2007) E	Altered maturation age and growth rate of populations due to fishing (Fairweather *et al.*, 2006; Hseih *et al.*, 2006) O	???
Ecosystem	Mesocosm experiments simulating the effect of individual drivers (e.g. ocean acidification, benthic: Christen *et al.* 2013; pelagic: Riebesell *et al.*, 2013) E, O or M	Mesocosm experiments studying differential effects of light and temperature, on copepods versus diatoms (Lewandowska and Sommer, 2010) E	Effects of fishing on ecosystem structure – trophic cascades (Frank *et al.*, 2005) O	Interplay of fishing and climate pressures on ecosystems promotes lower trophic levels (Kirby *et al.*, 2009) O; enhances diversity loss in benthic communities (Griffith *et al.*, 2011) M
Biome	Time-series observations on warming and the alteration of zooplankton biomes (Beaugrand *et al.*, 2009) O	???	???	???

Table 6-10: Challenges for the oceans that will arise from the employment of a range of geoengineering methods (SRM, solar radiation management, CDR, carbon dioxide removal).

Topic	Brief Description	Challenge and Impact	References
Solar radiation management techniques	Deflection of approximately 1.8 per cent of sunlight, by various techniques, is able to offset the global mean temperature effects of a doubling of atmospheric carbon dioxide content from preindustrial values	Will leave ocean acidification unabated (*high confidence*). Response of primary production to light reduction unclear.	Crutzen, 2006; Caldeira and Wood, 2008
Ocean storage by direct injection	Capture of CO_2 post-combustion from mainly coastal power plants, followed by injection of liquid CO_2 by pipeline or from a ship into the deep ocean.	Will add to ocean acidification and create localized harm to marine life (*high confidence*). Quantities will be small relative to the atmospheric invasion signal. CO_2 injected will dissolve and be transported by ocean circulation with eventual surface exposure.	Caldeira *et al.*, 2005
Sub-sea geologic storage	Capture of CO_2 from extracted gas or from post-combustion followed by well injection into a porous submarine aquifer beneath impermeable geologic strata.	Extensive experience in place from the Norwegian Sleipner field activity in the North Sea. No evidence of ocean impact from leakage to date.	Benson *et al.*, 2005
Ocean Fertilization	Spreading of trace amounts of reduced iron, over very large areas of the surface ocean where excess nutrients occur. Overcoming the local iron deficiency creates extensive phytoplankton blooms drawing down sea surface pCO_2. Fertilization can also be carried out by using direct or indirect (ocean pipes) addition of macronutrients to oceanic regions where they are depleted.	Much of the exported organic matter is remineralized at shallow depths creating local oxygen stress and shallow CO_2 enrichment, methane and N_2O production. These effects are temporary and the effective retention time is short. If sustained, reduced surface-ocean and increased deep-ocean acidification. O_2 loss in ocean interior (*medium confidence*).	de Baar *et al.*, 1995; de Baar *et al.*, 2005; Pörtner *et al.*, 2005; Boyd *et al.*, 2007; Buesseler *et al.*, 2008; Law, 2008; Cao and Caldeira, 2010
Artifical upwelling or downwelling	Ocean fertilization by bringing nutrient rich deep water (from 200 - 1000 m) to the surface. Downwelling occurs in parallel, transporting physically dissolved CO_2 into the deep ocean.	Deep water contains high levels of CO_2, which if released counteracts the binding of CO_2 by fertilization. No evidence available.	Lovelock and Rapley, 2007 Oschlies *et al.*, 2010
Sequestration of organic carbon	Storage of terrestrial biomass in the coastal or deep ocean	Physical impact, regional loss of oxygen, CO_2 accumulation and acidification during degradation, increases in methane, N_2O and H_2S. No evidence available.	Metzger and Benford, 2001; Strand and Benford, 2009
Carbonate neutralization	Dissolution of power plant flue gas into sea water yielding an acidic solution which is neutralized by addition of crushed limestone. The resulting bicarbonate rich fluid is discharged to the ocean.	Involves the transport and crushing to fine scale of large quantities of limestone and the processing of very large quantities of sea water. Environmental impact issues not yet explored.	Rau, 2011
Accelerated olivine weathering	Uses wind powered electrochemical processes to remove HCl from the ocean and neutralizes the acid with silicate minerals such as olivine for disposal. The net result is to add alkalinity to the ocean akin to natural silicate weathering processes.	Complex system as yet untested in pilot processes. Involves mining and crushing large quantities of silicate minerals. Very long time scale consequences uncertain.	House *et al.*, 2007; Köhler *et al.*, 2010

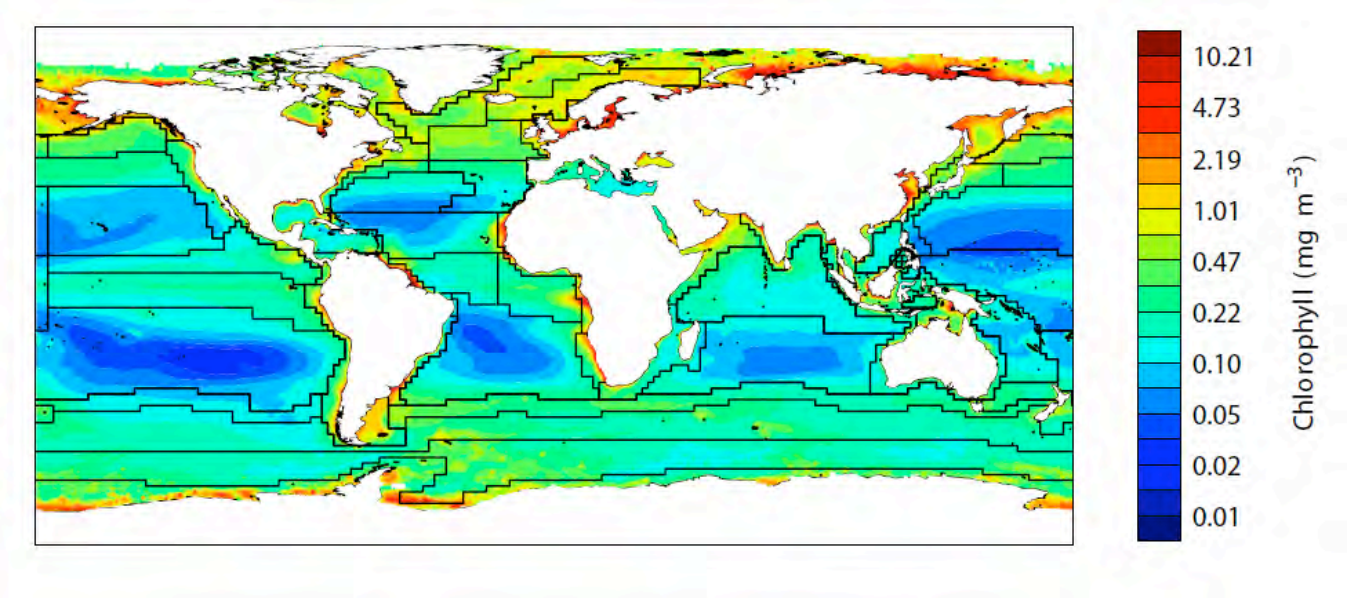

Figure 6-1: Productivity in 51 distinct global ocean biogeographical biomes as represented by a grid of thin black lines (after Longhurst, 1998), overlain with an average annual composite plot of chlorophyll *a* concentration, i.e., a proxy for phytoplankton stocks in the upper ocean, from the NASA/Orbimage SeaWiFs satellite (Bailey *et al*., 2006; McClain *et al*., 2004; McClain, 2009). The characteristics and boundaries of each biome are primarily set by the underlying regional ocean physics and chemistry. Together, these provinces or biomes span several orders of magnitude in chlorophyll *a* from < 0.1 mg m^{-3} that characterize the low latitude oligotrophic regions (denoted by purple and blue) up to 10 mg m^{-3} in highly productive coastal upwelling regions in Eastern boundary currents (denoted by red).

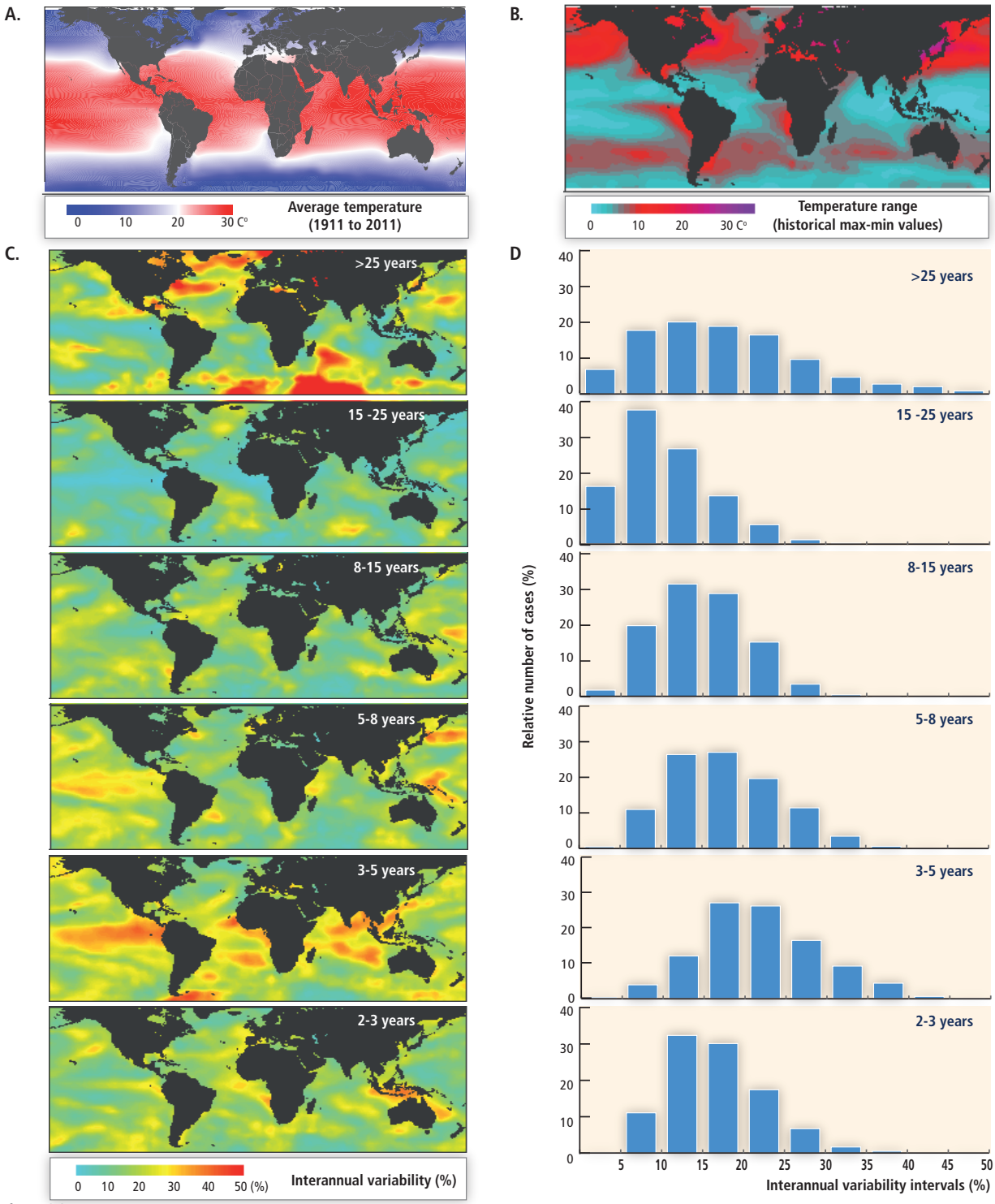

Figure 6-2 | Last Century sea surface temperature variability. A) The long term (1911 to 2011) sea surface temperature average. B) The temperature range calculated as the difference between the historical maximum and minimum values for each grid component. C) The spatial distribution of variability by time scales was computed by accumulating the relative spectral densities of each 2°x2° grid box frequency-transformed series by frequency windows, corresponding to the multidecadal (period >25 years), bidecadal (15 to 25 years), decadal (8 to 15 years), low ENSO frequency (5 to 8 years), high ENSO frequency (3 to 5 years) and very high frequency (2 to 3 years) scales. The sum of the six maps at every single box corresponds to 100% of the interannual time series variability. D) The relative number of cases (grid boxes) at each temperature class intervals. The class intervals represent fractions of the temperature range at each variability scale. The sum of all cases for each histogram accounts of the 100% of the area, and the sum of all the temperature fractions from all histograms accounts for the total temperature ranges shown in the upper right map. All computations are based on the Extended Reynolds Sea Surface Temperature (NOAA, 2012).

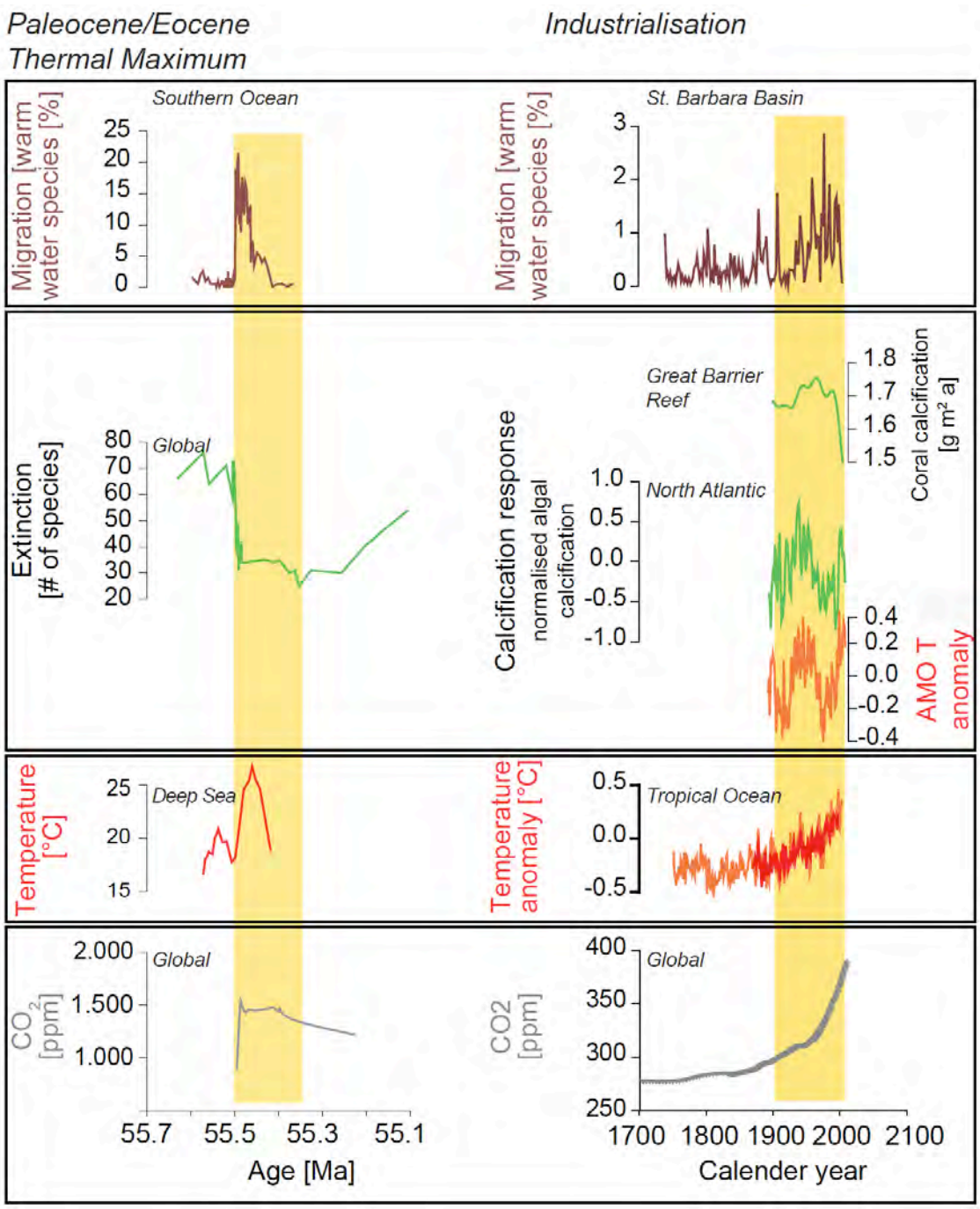

Figure 6-3: Atmospheric CO_2 (bottom, grey) and temperature (middle, red/orange) changes with associated biotic changes (top) for the Paleocene Eocene Thermal Maximum (PETM) and the industrial era. Episodes of largest environmental change are indicated with yellow bars. CO_2 data are based on measurements at Mauna Loa (modern: Keeling *et al.*, 2005) and model output (PETM: Ridgwell and Schmidt, 2010; Zeebe *et al.*, 2009). Temperature data are based on proxy data (modern: Wilson *et al.*, 2006; Lea *et al.*, 2003; PETM: Kennett and Stott, 1991) representing the regional temperature changes in the surface ocean. Modern biotic responses include changes in coralline algal growth (Halfar *et al.*, 2011), and coral calcification (De'ath *et al.*, 2009). Evolutionary changes are exemplified by the extinction of benthic foraminifera (Thomas, 2003). Abundance data (top row) of planktonic foraminifera and coccolithophores (modern: Field *et al.*, 2006; PETM: Bralower, 2002) indicate range expansion due to warming.

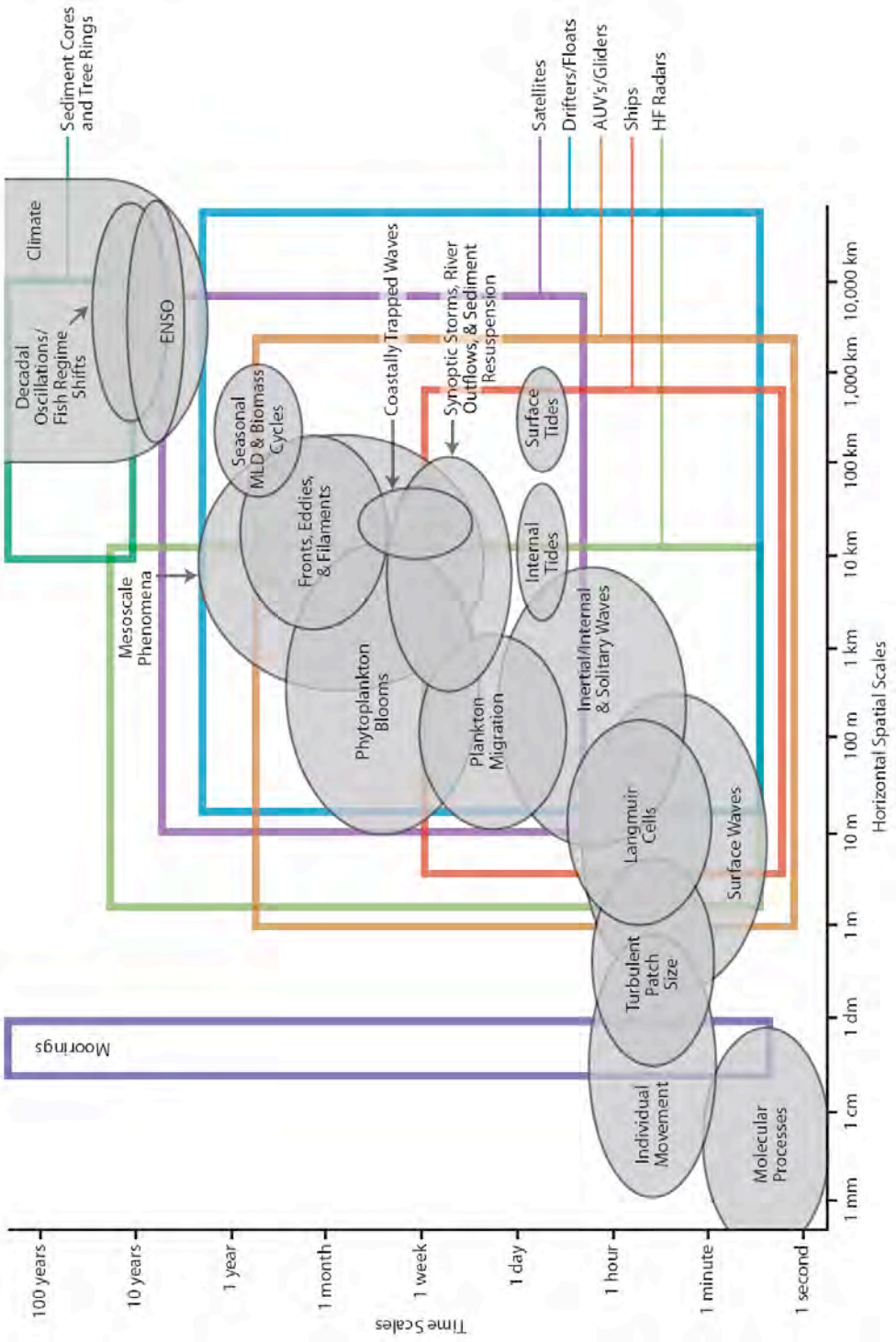

Figure 6-4: Multiple coupled temporal and spatial scales of variability in physical, physiological and ecological processes of interest in contemporary marine system research. Observations over broad time and space scales are necessary to separate natural variability from impacts due to human-induced effects, and define the observation tools that are necessary to obtain relevant data. The shaded regions depict the approximate boundaries of major processes of interest, and the boxes define the scales of selected measurement/observation procedures. Langmuir cells are a series of wind-driven shallow, slow, counter-rotating circulations at the ocean's surface. From Karl (2010), as modified from Dickey (1991).

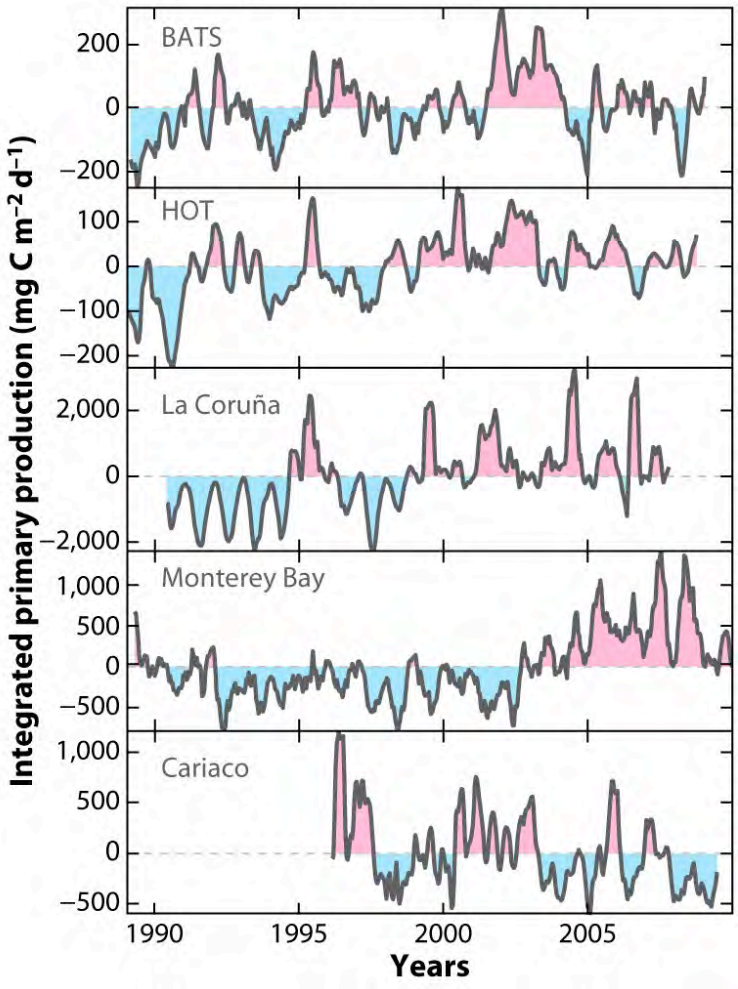

Figure 6-5: Time-series of water column integrated primary production (PP) anomalies at: Northwestern Spain, La Coruña (43° 25.2 N, 8° 26.4 E); HOT (22° 45 N, 158°W); BATS (31° 50 N, 64° 10 W); Monterey Bay, Central California Current (37°N, 122°W); Cariaco Basin, Venezuela (10°30 N, 64°40 W), reproduced from Chavez *et al.* (2011). Anomalies were calculated by integrating over the water column, then interpolating to 14 d, smoothing with a moving average and differencing for each 14-d interval from the grand mean for that interval. All sites except Cariaco seem to show positive (pink) PP anomalies after 2000.]

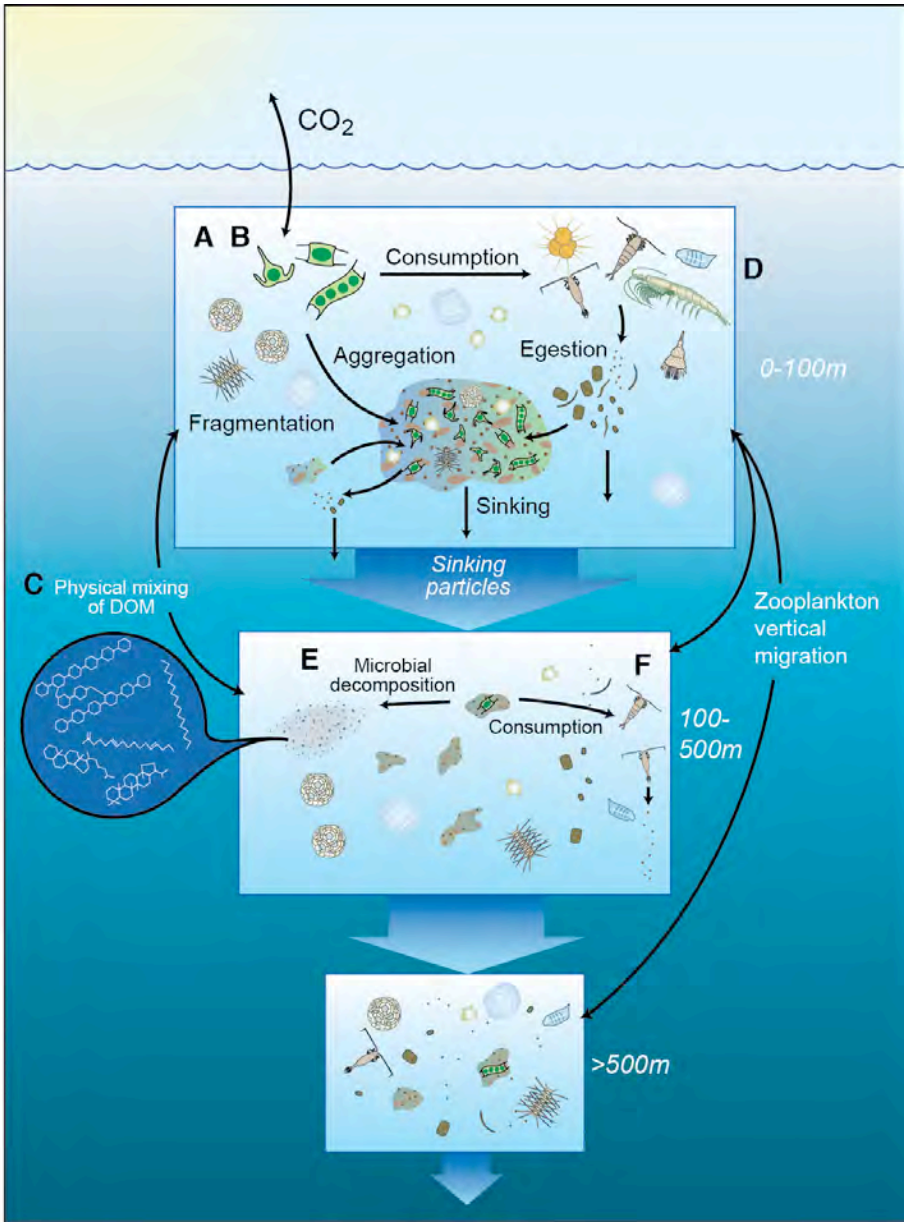

Figure 6-6: A schematic representation of the ocean's biological pump, which responds to climate change and is a relevant conduit for carbon sequestration. It is difficult to project how the pump might be altered (Table 6-4) and whether it would represent a positive or negative feedback to climate change which causes: A, shifts in NPP (Net Primary Production; Bopp *et al.*, 2002); B, floristic and faunistic shifts in the pelagic (Beaugrand *et al.*, 2009) that may alter the relationship between OA and ballasting of settling particles (Klaas and Archer, 2002); C, changes in proportion of NPP released as DOM (Dissolved Organic Matter) due to the effects of ocean acidification (Engel *et al.*, 2004); E, warming and faster bacterial enzymatic rates of particle solubilization (Christian and Karl, 1995); and faunistic shifts at depth (Jackson and Burd, 2001). Modified from Buesseler *et al.* (2008) by J. Cook (WHOI).

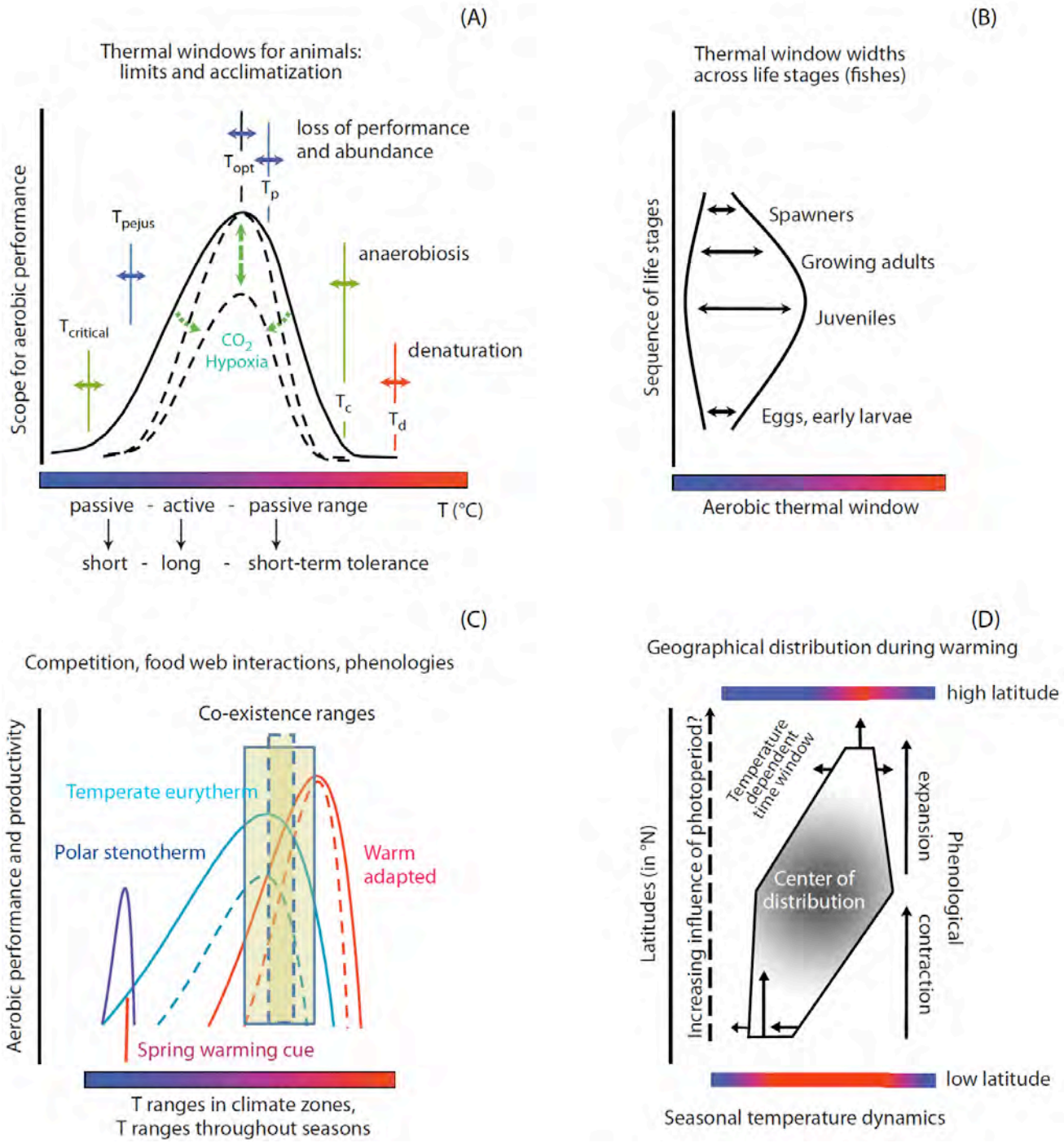
(A)
Thermal windows for animals: limits and acclimatization
loss of performance and abundance
T_{opt}
T_p
T_{pejus}
anaerobiosis
$T_{critical}$
CO_2 Hypoxia
denaturation
T_c
T_d
Scope for aerobic performance
passive - active - passive range
T (°C)
short - long - short-term tolerance
(B)
Thermal window widths across life stages (fishes)
Sequence of life stages
Spawners
Growing adults
Juveniles
Eggs, early larvae
Aerobic thermal window
(C)
Competition, food web interactions, phenologies
Co-existence ranges
Temperate eurytherm
Polar stenotherm
Warm adapted
Spring warming cue
Aerobic performance and productivity
T ranges in climate zones,
T ranges throughout seasons
(D)
Geographical distribution during warming
high latitude
Temperature dependent time window
Increasing influence of photoperiod?
Latitudes (in °N)
expansion
contraction
Phenological
Center of distribution
low latitude
Seasonal temperature dynamics

Figure 6-7

Figure 6-7: Mechanisms linking organism to ecosystem response explain the why, how, when and where of climate sensitivity (based on knowledge for animals, after Pörtner, 2001, 2002a, 2012; Pörtner and Farrell, 2008, blue to red colour gradients illustrate transition from cold to warm temperatures). (A) As all biota, animals specialize on limited temperature ranges, within which they grow, behave, reproduce, defend themselves by immune responses. Optimum temperatures (T_{opt}) indicate performance maxima, pejus temperatures (T_p) the limits to long-term tolerance, critical temperatures (T_c) the transition to anaerobic metabolism, and denaturation temperatures (T_d) the onset of cell damage. These OCLTT thresholds (see text) can shift by acclimatization (horizontal arrows). Under elevated CO_2 levels and in hypoxic waters performance levels can decrease and windows of performance be narrowed (dashed green arrows pointing to dashed black curves). (B) Thermal range widths (horizontal arrows) change between individual life stages of a species. (C) The shift of performance curves between polar, temperate and tropical animal species reflect evolutionary adaptation to the respective climate zones. Via species-specific effects on performance (dashed curves, cf. A), additional stressors and species interactions cause shifts in higher-level processes (seasonal activities in response to light or temperature cues, shifts in predator-prey interactions and competition within changing coexistence ranges of interacting species). (D) Shifts in biogeography result during climate warming (modified after Beaugrand, 2009). The polygon delineates the range in space and time, the level of grey denotes abundance. Species display maximum productivity in southern spring, wide seasonal coverage in the centre and a later productivity maximum in the North. The impact of photoperiod increases with latitude (dashed arrow). During warming, the southern temperature and time window contracts while the northern one dilates (directions and shifts indicated by arrows). Control by water column characteristics or photoperiod may overrule temperature control in some organisms (e.g. diatoms), causing contraction of spatial distribution in the north.

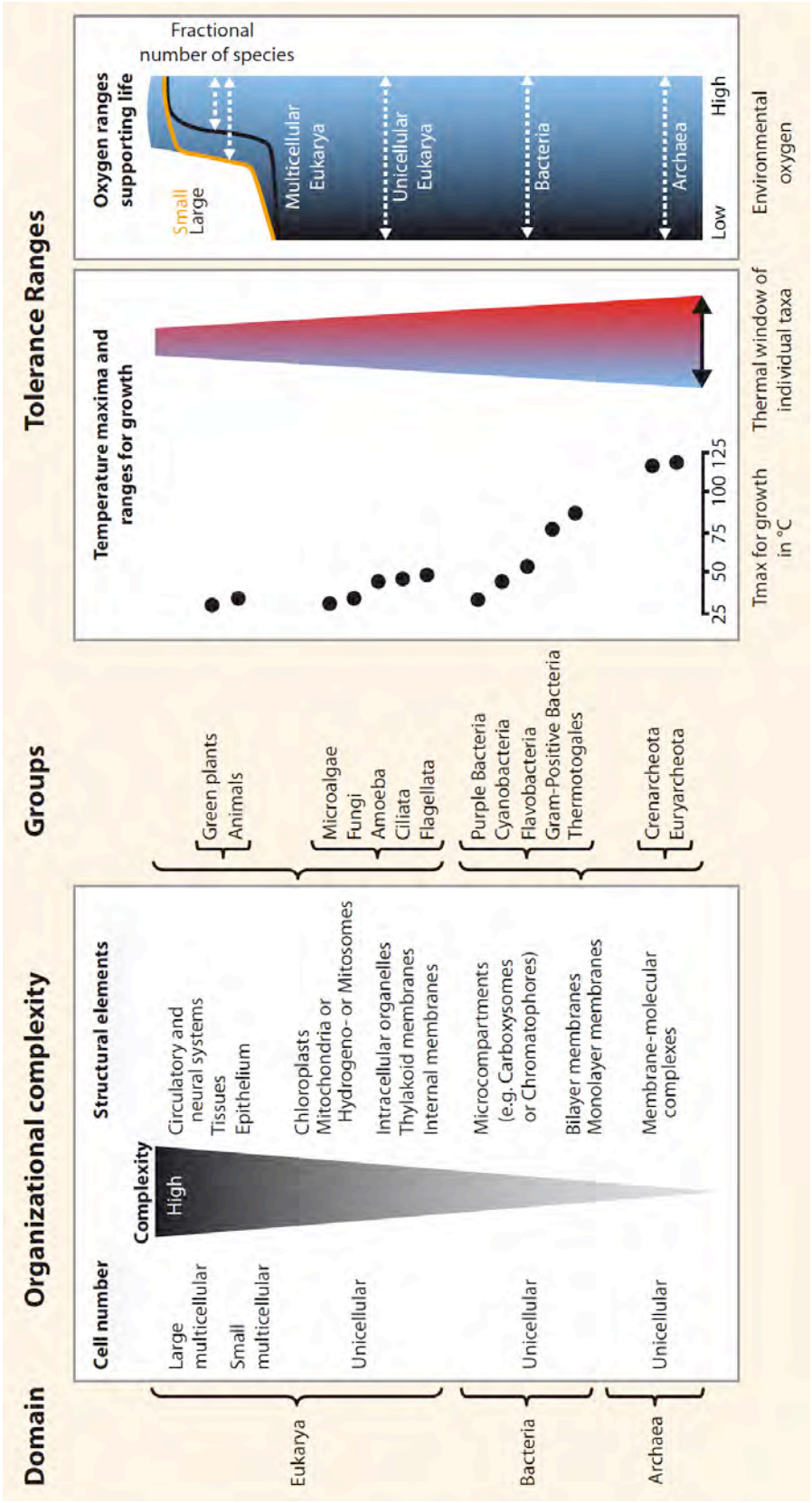
Domain
Organizational complexity
Groups
Tolerance Ranges
Cell number
Structural elements
Complexity
High
Large multicellular
Small multicellular
Unicellular
Unicellular
Unicellular
Circulatory and neural systems
Tissues
Epithelium
Chloroplasts
Mitochondria or Hydrogeno- or Mitosomes
Intracellular organelles
Thylakoid membranes
Internal membranes
Microcompartments (e.g. Carboxysomes or Chromatophores)
Bilayer membranes
Monolayer membranes
Membrane-molecular complexes
Eukarya
Bacteria
Archaea
Green plants
Animals
Microalgae
Fungi
Amoeba
Ciliata
Flagellata
Purple Bacteria
Cyanobacteria
Flavobacteria
Gram-Positive Bacteria
Thermotogales
Crenarcheota
Euryarcheota
Temperature maxima and ranges for growth
25 50 75 100 125
Tmax for growth in °C
Thermal window of individual taxa
Oxygen ranges supporting life
Fractional number of species
Small
Large
Multicellular Eukarya
Unicellular Eukarya
Bacteria
Archaea
Low
High
Environmental oxygen

Figure 6-8

Figure 6-8: Ranges of temperatures and O_2 concentrations covered by various domains and groups of free living marine organisms (bacteria to animals, domains and groups modified after Woese *et al*.,1990) in various habitats (Storch *et al*., subm.). High organizational complexity enables an increase in body size, associated with decreasing tolerances to hypoxia and heat. In the domain Bacteria, the group Thermotogales comprises obligate anaerobes, displays less complex structures such as a single layer lipid membrane and is most tolerant to high temperatures. Highest temperatures of growth were found at 122°C in hydrothermal vent species under elevated hydrostatic pressure in laboratory experiments. Dashed white arrows denote wide O_2 tolerances in unicellular archeae, bacteria and protists, as compared to animals and plants (multicellular eukarya). Anoxic habitats are conquered by small multicellular and unicellular Eukarya, supported by less complex mitosomes or hydrogenosomes used in energy metabolism. Species richness of animals (upper right) increases with rising O_2 levels reflecting better hypoxia tolerance in small compared to large individuals and their taxa (6.3.3.).

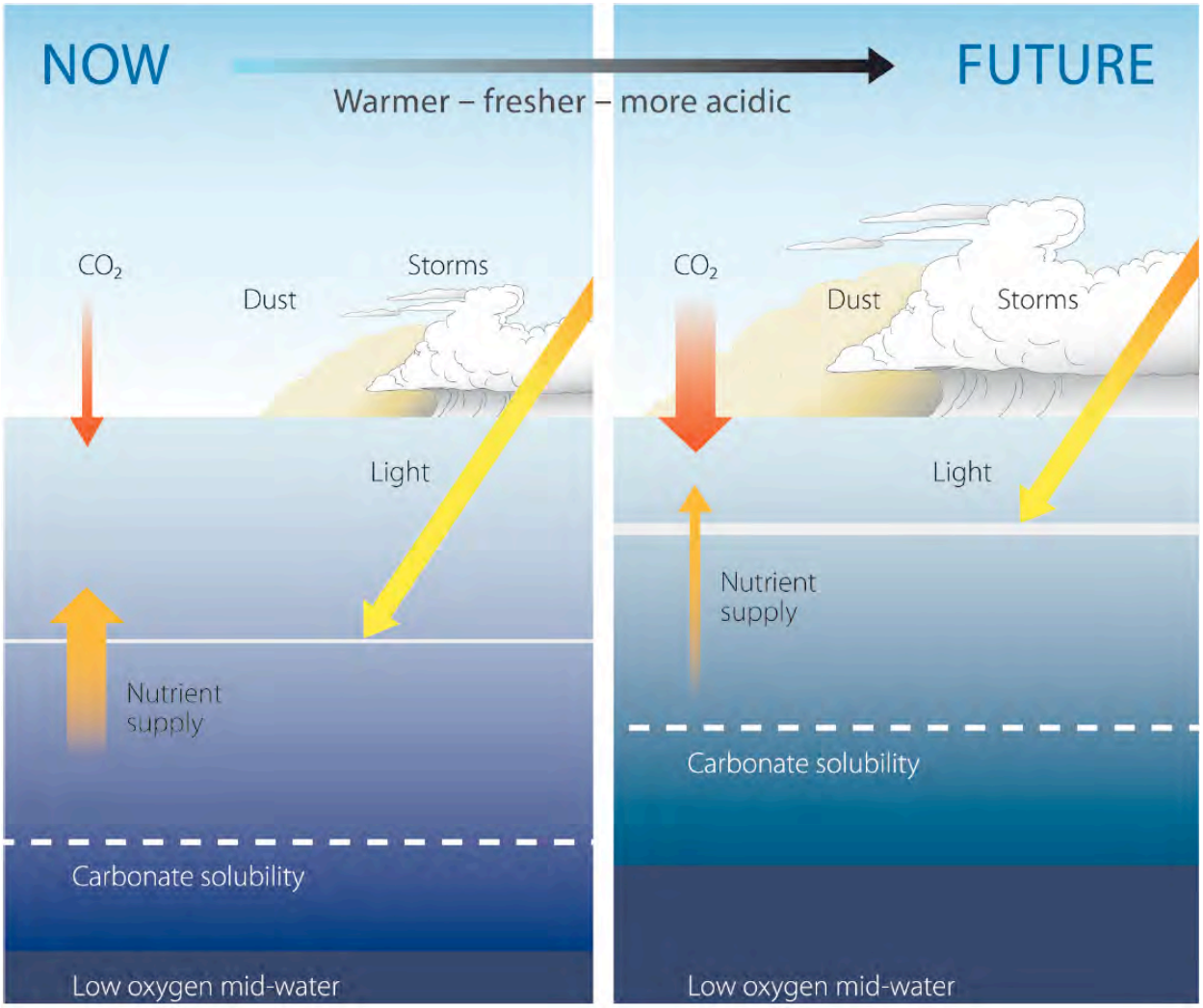

Figure 6-9: Projected alteration of oceanic properties and atmospheric events due to a changing climate. Properties will be altered across the water column, from the mid-water stratum to the sunlit surface layer, and will influence the fitness of the residence biota. Changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean ecosystems (courtesy of Boyd and Law, 2011).

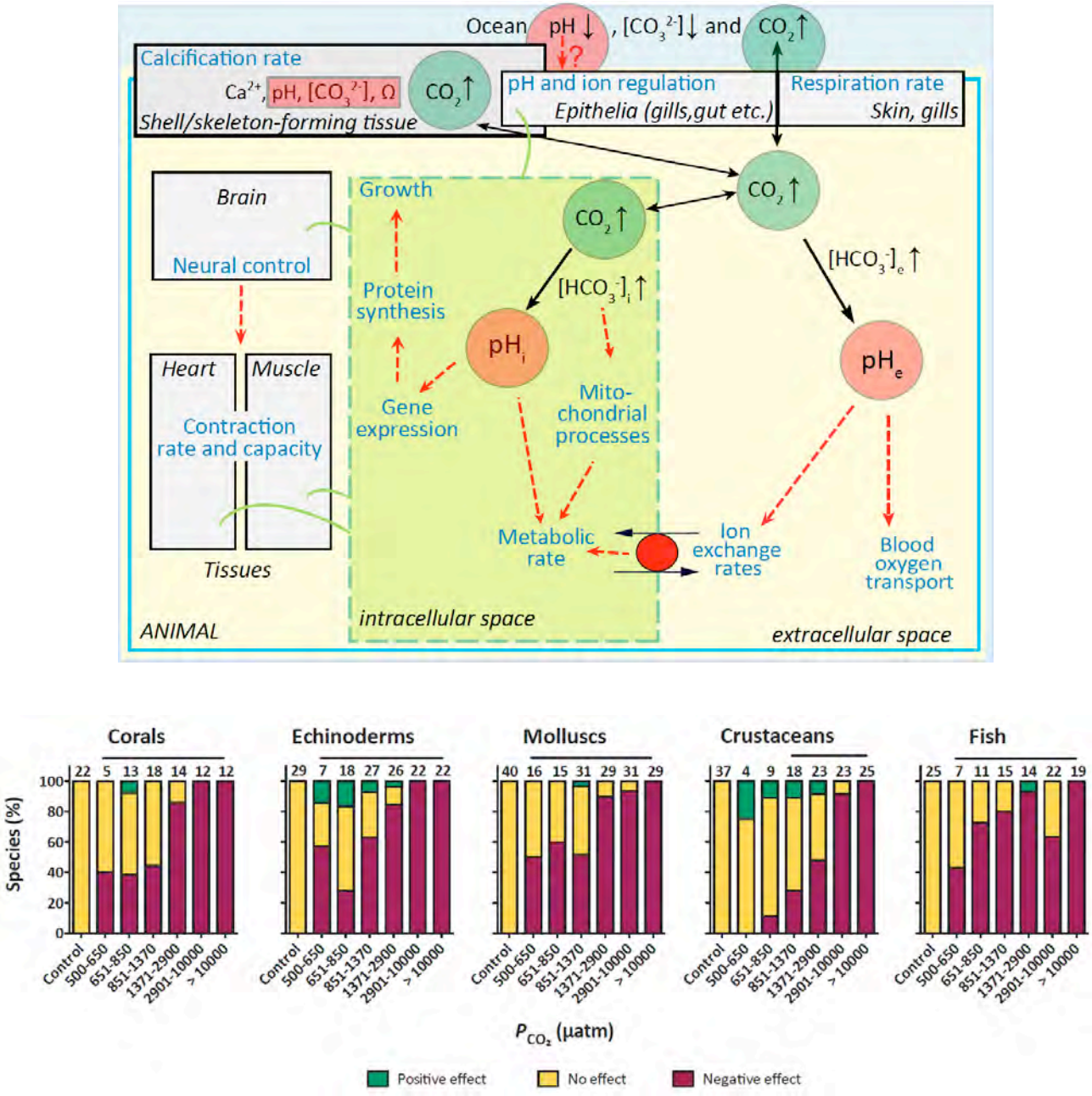

Figure 6-10: Top: Responses of a schematized marine animal (blue line) to ocean acidification (OA). Effects are mediated via diffusive entry of accumulating CO_2 (dark green, black arrows) into body compartments, resulting in a drop in compartmental pH (highlighted in red) and its effects (red dashed arrows) on various processes (light blue) as well as calcium carbonate saturation state (Ω) at calcification sites (after Pörtner, 2008). Variable sensitivity depends on the degree of pH decline and compensation, depending on the capacity of transmembrane ion transport. Bottom: % fraction of studied scleractinian coral, echinoderm, molluscan, crustacean and fish species affected negatively, positively or not at all by various levels of ambient CO_2. Effects considered include those on life stages and processes reflecting physiological performance (O_2 consumption, aerobic scope, behaviours, scope for behaviours, calcification,

growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, morphology). As not all life stages, parameters and pCO_2 ranges were covered in all species two assumptions partially compensate for missing data: 1) Negative effects at low pCO_2 will remain negative at high pCO_2. 2) A positive or neutral outcome at both low and high pCO_2 will be the same at intermediate pCO_2. As responses reported for each species vary for each CO_2 range, variable species numbers result (on top of columns). The total number of species studied for a given group is represented as the number above the control column. Horizontal bars above columns represent frequency distributions significantly different from controls (from Wittmann and Pörtner, subm.).

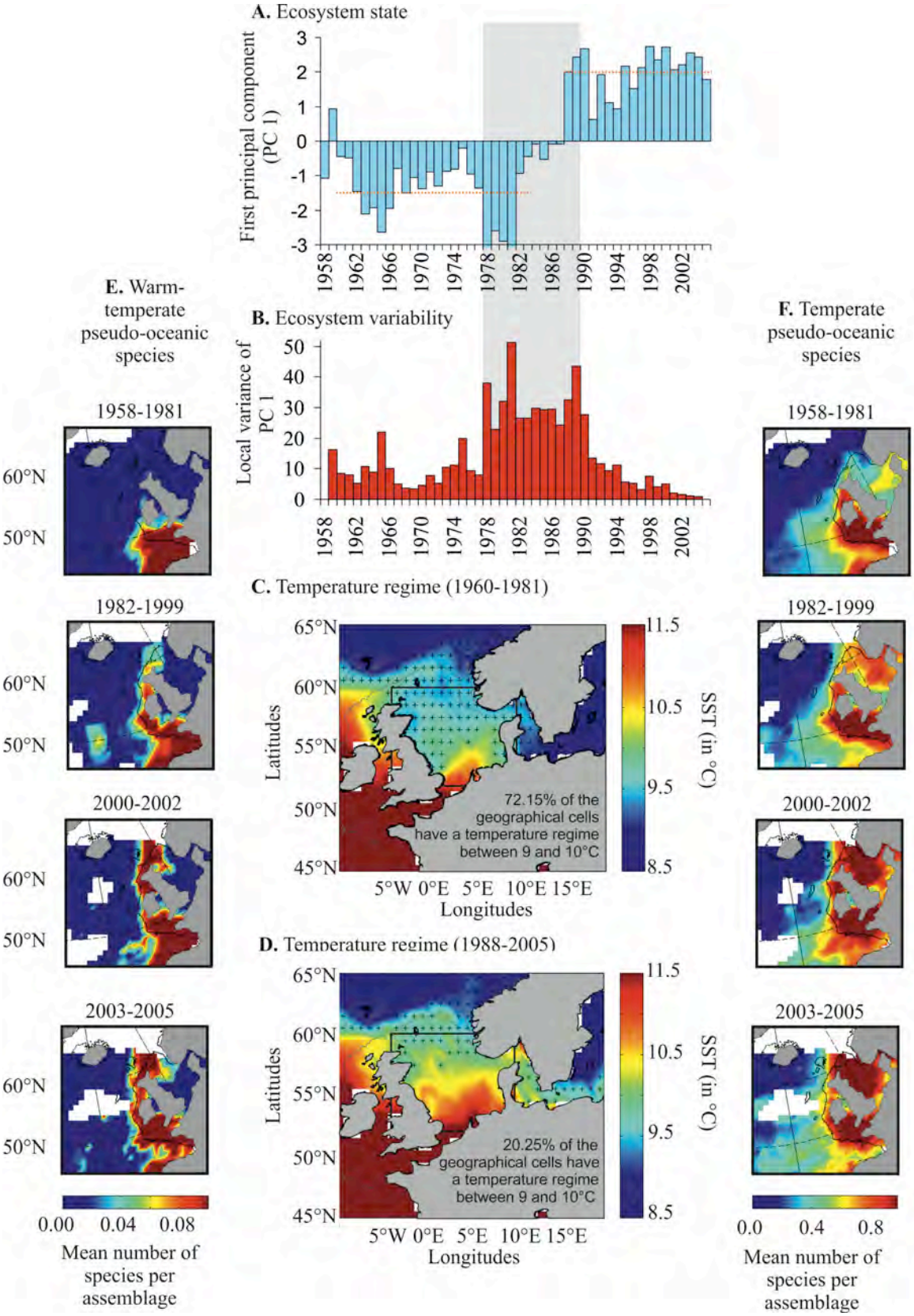
A. Ecosystem state
First principal component (PC 1)
B. Ecosystem variability
Local variance of PC 1
C. Temperature regime (1960-1981)
D. Temperature regime (1988-2005)
72.15% of the geographical cells have a temperature regime between 9 and 10°C
20.25% of the geographical cells have a temperature regime between 9 and 10°C
Latitudes
Longitudes
SST (in °C)
E. Warm-temperate pseudo-oceanic species
F. Temperate pseudo-oceanic species
1958-1981
1982-1999
2000-2002
2003-2005
Mean number of species per assemblage

Figure 6-11

Figure 6-11: **A**. Long-term changes in the ecosystem state based on 5 biological parameters (phytoplankton colour index, mean size of calanoids, mean calanoid diversity, an index of change in plankton composition and cod recruitment). The orange line denotes the mean ecosystem state for the period prior and after the abrupt ecosystem shift. **B**. Long-term changes in the multiscale temporal local variance of the ecosystem state (in red). High values indicate pronounced year-to-year changes in the ecosystem state. The light gray band shows the unstable period (1980-1989). **C**-**D**. Observed mean annual sea surface temperature in the North Sea during 1960-1981 (**C**) and 1988-2005 (**D**). The location of the critical thermal boundary (9-10°C) is indicated by '+'. **E.** Long-term changes in the mean number of warm-temperate pseudo-oceanic species from 1958 to 2005. **F.** Long-term changes in the mean number of temperate pseudo-oceanic species from 1958 to 2005. The period 1958-1981 was a period of relative stability and the period 1982-1999 was a period of rapid northward shifts, indicating that the abrupt ecosystem shift observed in the North Sea was part of a large-scale response of the zooplankton biodiversity to warming temperatures (see **A**-**D**). Average values are below 1 because they are annual averages. Note that the color bar is 10-fold smaller for warm-temperate pseudo-oceanic species because these species are less frequently observed than their temperate counterparts. From Beaugrand *et al*. (2008) and Beaugrand *et al*. (2009).

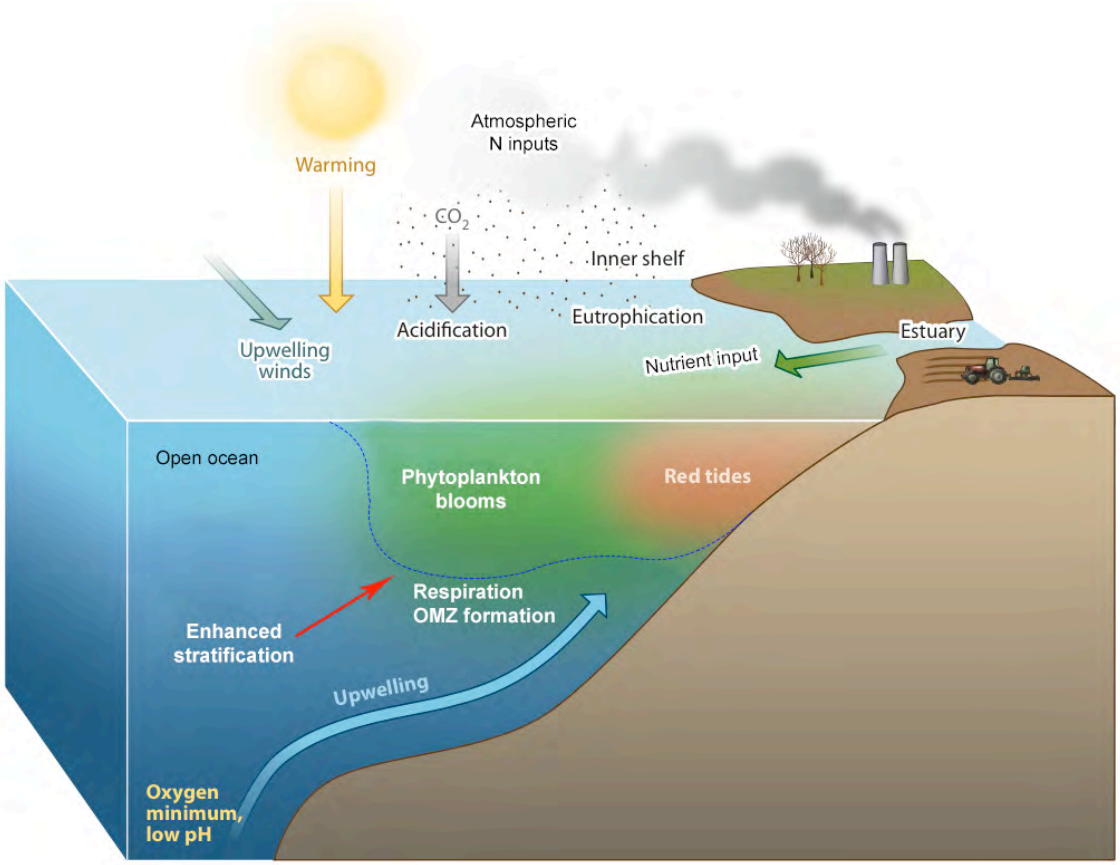

Figure 6-12: Schematic illustrating the principal mechanisms underlying the formation of hypoxic conditions and their biological background (modified from Levin *et al.* 2009; Levin and Sibuet, 2012). The buoyancy flux from fluvial discharges produces sharp density stratification at the base of the freshened layer (also valid for icemelt, high precipitation) near the surface and, hence, vertical mixing is greatly reduced. In consequence, the nutrient inputs from the river and the atmosphere accumulate in a narrow upper layer, leading to phytoplankton blooms. The enhancement of oxygen consumption due to respiratory catabolism of sinking organic matter results in hypoxic conditions of OMZs. Heating of the upper layer further increases stratification, while the wind-driven upwelling of hypoxic, nutrient-rich water from deeper layers adds to the formation of the oxygen minimum zone.

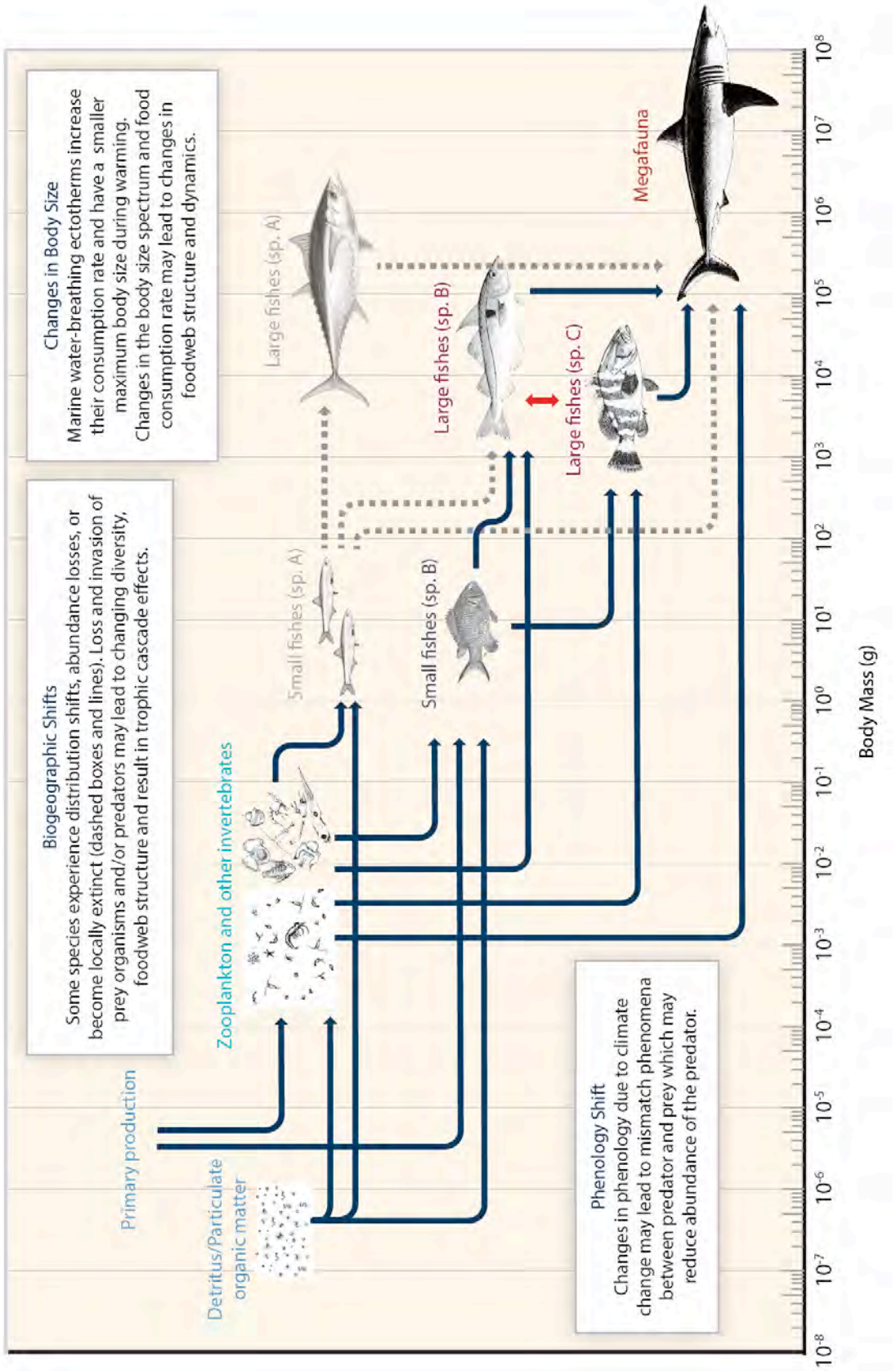
Changes in Body Size
Marine water-breathing ectotherms increase their consumption rate and have a smaller maximum body size during warming. Changes in the body size spectrum and food consumption rate may lead to changes in foodweb structure and dynamics.
Biogeographic Shifts
Some species experience distribution shifts, abundance losses, or become locally extinct (dashed boxes and lines). Loss and invasion of prey organisms and/or predators may lead to changing diversity, foodweb structure and result in trophic cascade effects.
Phenology Shift
Changes in phenology due to climate change may lead to mismatch phenomena between predator and prey which may reduce abundance of the predator.
Primary production
Detritus/Particulate organic matter
Zooplankton and other invertebrates
Small fishes (sp. A)
Small fishes (sp. B)
Large fishes (sp. A)
Large fishes (sp. B)
Large fishes (sp. C)
Megafauna
Body Mass (g)
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}

Figure 6-13

Figure 6-13: Schematic diagram of a marine foodweb and the expected responses to climate change including ocean acidification. A coupled pelagic and benthic foodweb is typically structured by the body size spectrum of species. Warming, hypoxia and ocean acidification lead to biogeographical shifts, changes in species abundance and in the dynamics of trophic interactions. The foodweb resulting from climate change includes reductions in the body size of organisms, changes in species composition and the resulting reconfiguration of trophic linkages. Fishing generally removes large-bodied and vulnerable species and truncates the body size spectrum of the community. As a result, the detection and attribution of foodweb responses to climate change are strongly confounded by fishing effects. The arrows represent species interactions (e.g., between predator and prey or competition for food or space). Broken lines (boxes and arrows) indicate the loss of populations and trophic linkages due to climate change.

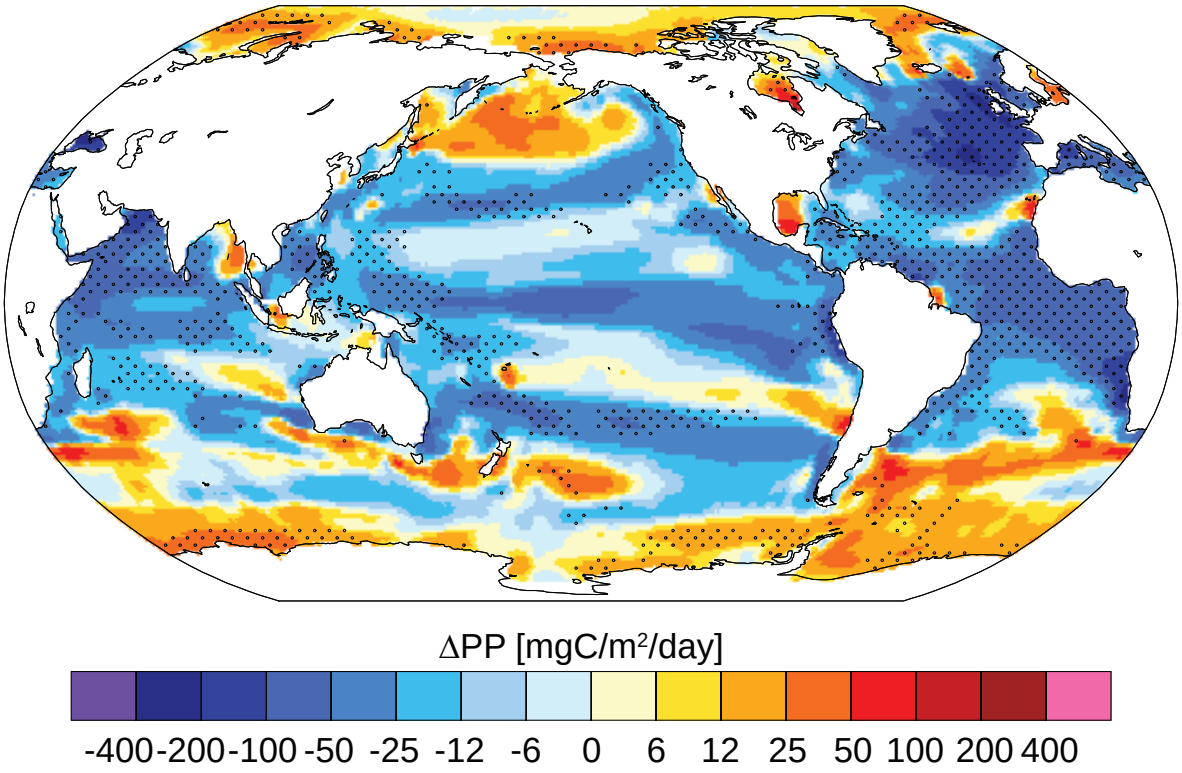

Figure 6-14: Multi-model mean changes of projected vertically-integrated net primary production (small and large phytoplankton). To indicate consistency in the sign of change, regions are stippled where all four models agree on the sign of change. Changes are annual means under the SRES A2 scenario (between RCP6.0 - 8.5) for the period 2080 to 2099 relative to 1870 to 1889, after Steinacher *et al.* (2010).

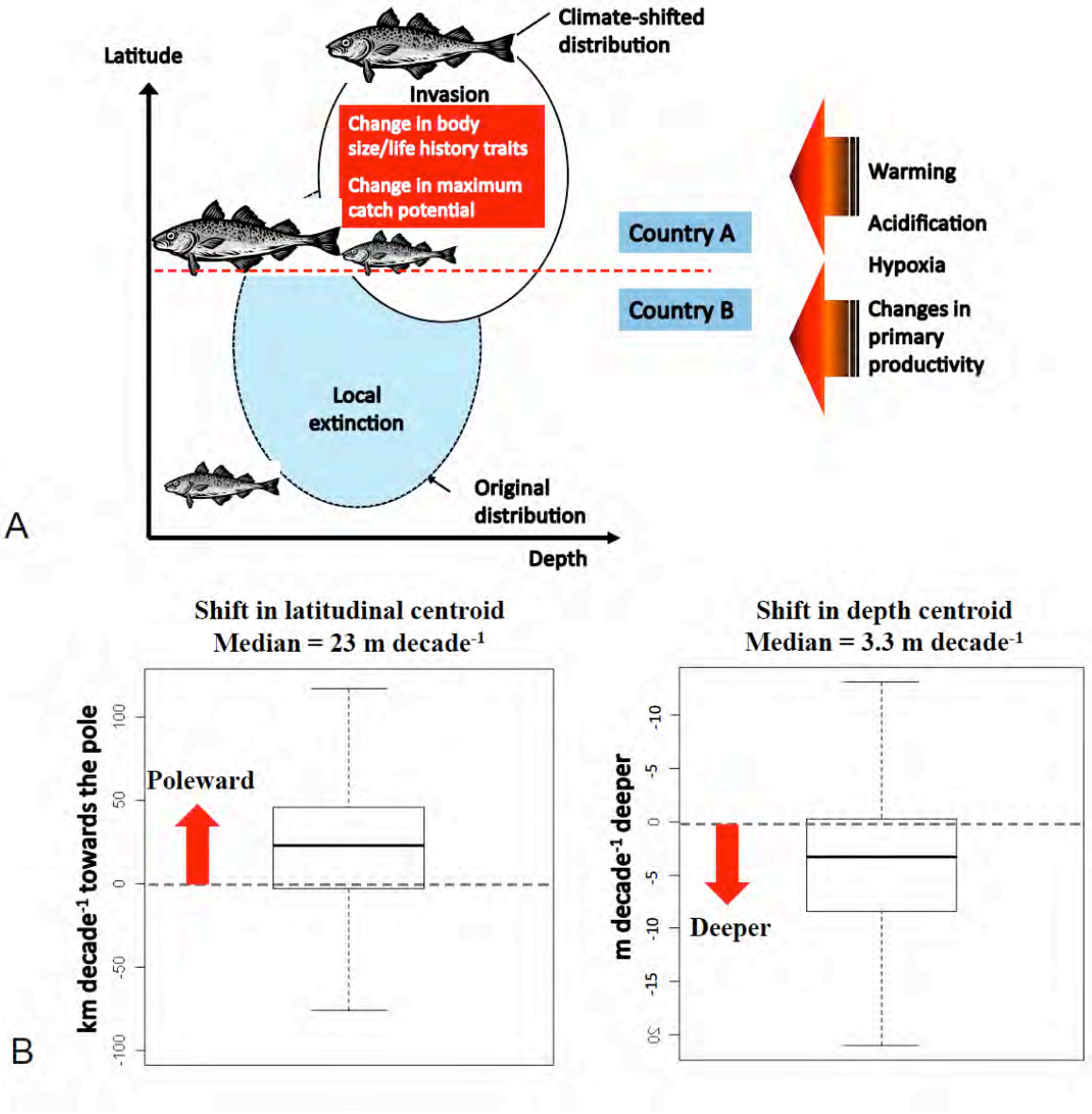

Figure 6-15 A, B

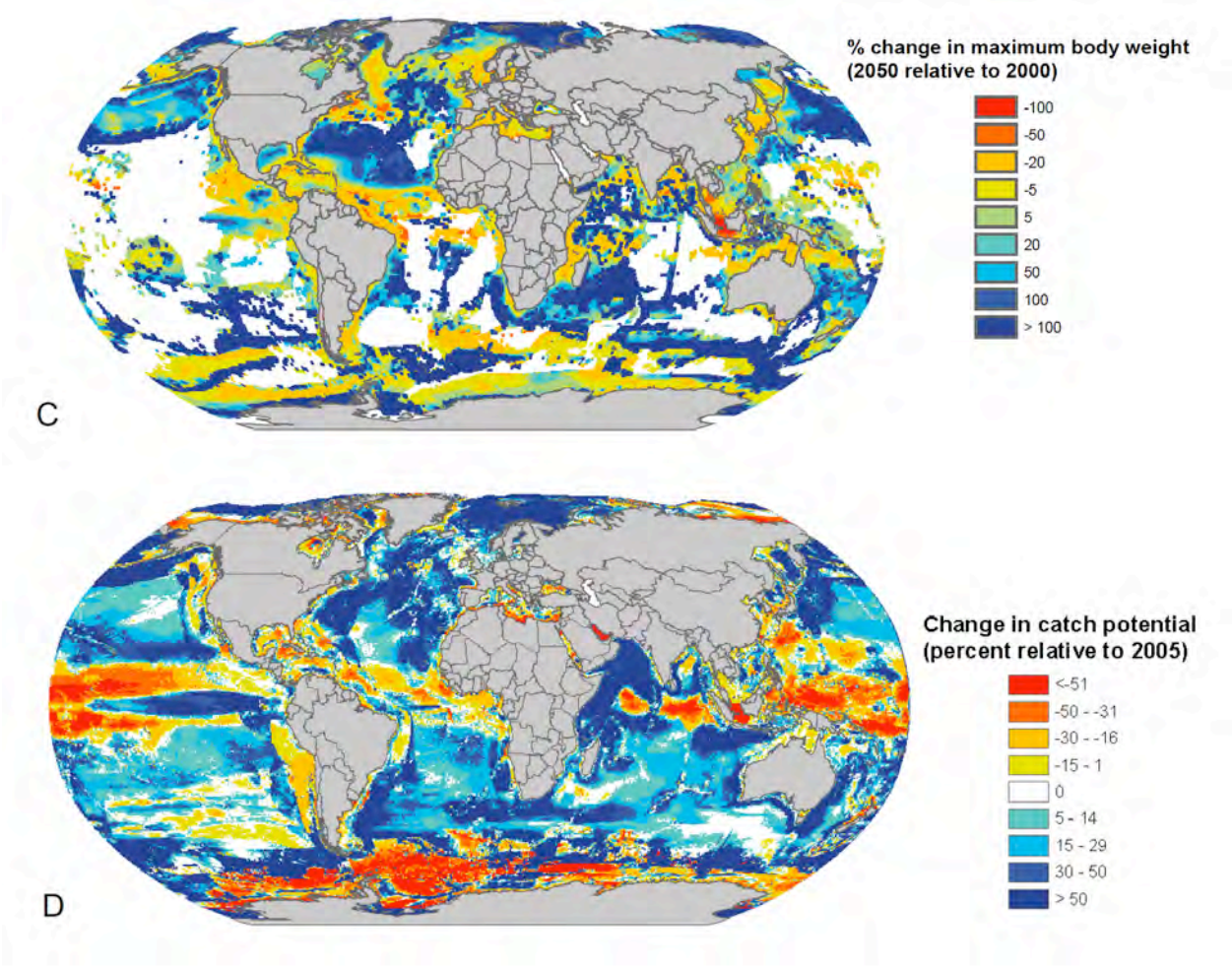

Figure 6-15: Scenarios of climate change effects on the biogeography, biology and fisheries catch potential of marine fishes and invertebrates. (A) Hypothesis of changes in distribution, biology and fisheries catch potential of fish stocks under climate change. (B) Example of a projected rate of shift in distribution range along latitude and depth for 610 exploited demersal fish species from 1991-2010 to 2041 – 2060 under the SRES A2 scenario (Cheung et al., 2011; Cheung et al., 2012a). (C) Projected change in the maximum body size of 610 species of marine fishes from 2000 to 2050 under the SRES A2 (between RCP6.0 - 8.5) scenario (Cheung et al. 2012a). The white area is not occupied by the sampled species. (D) Example of projections of maximum fisheries catch potential of 1000 species of exploited fishes and invertebrates from 2000 to 2050 under the SRES A1B scenario (redrawn from Cheung et al., 2010)

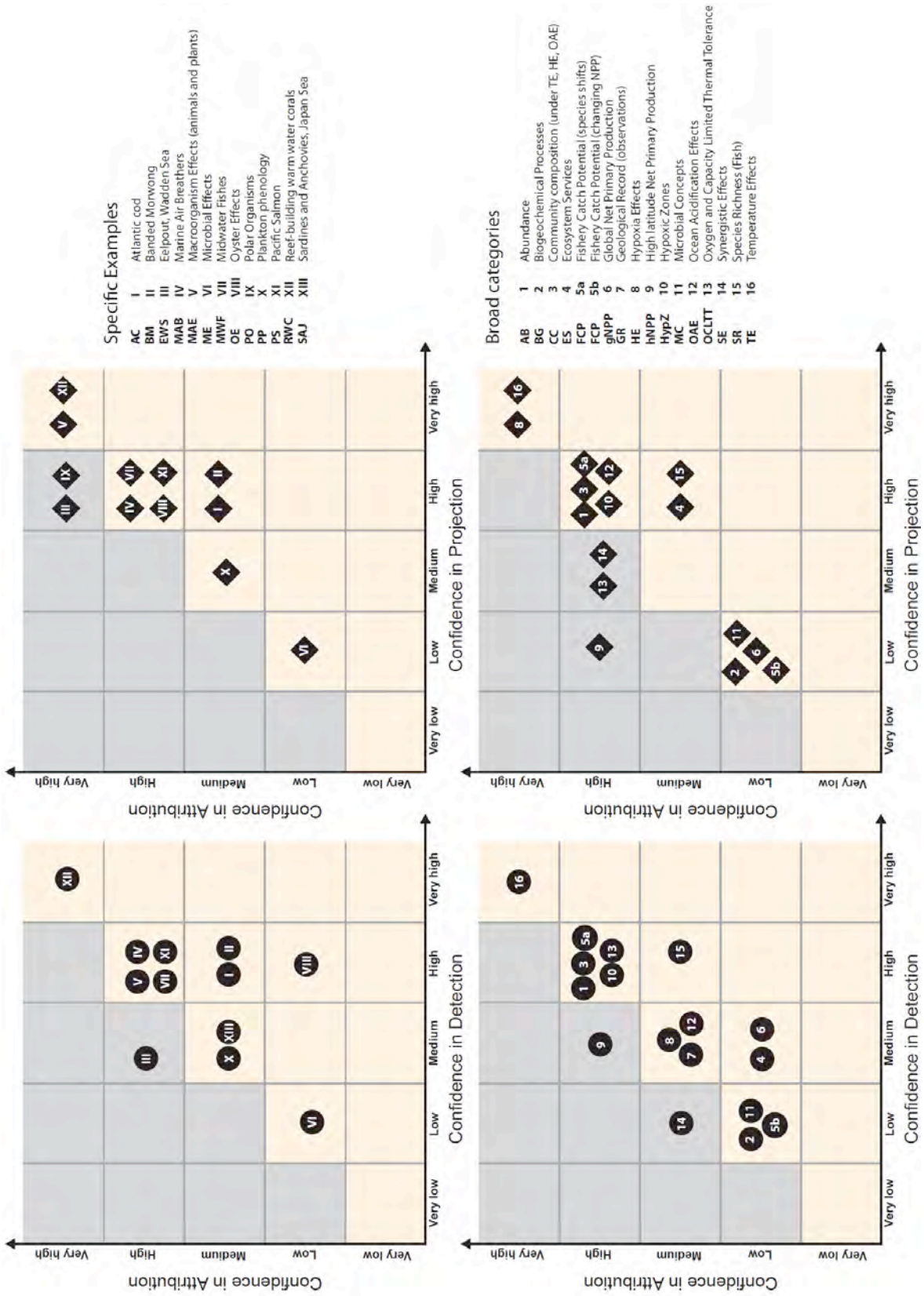
Specific Examples
AC I Atlantic cod
BM II Banded Morwong
EWS III Eelpout, Wadden Sea
MAB IV Marine Air Breathers
MAE V Macroorganism Effects (animals and plants)
ME VI Microbial Effects
MWF VII Midwater Fishes
OE VIII Oyster Effects
PO IX Polar Organisms
PP X Plankton phenology
PS XI Pacific Salmon
RWC XII Reef-building warm water corals
SAJ XIII Sardines and Anchovies, Japan Sea
Broad categories
AB 1 Abundance
BG 2 Biogeochemical Processes
CC 3 Community composition (under TE, HE, OAE)
ES 4 Ecosystem Services
FCP 5a Fishery Catch Potential (species shifts)
FCP 5b Fishery Catch Potential (changing NPP)
gNPP 6 Global Net Primary Production
GR 7 Geological Record (observations)
HE 8 Hypoxia Effects
hNPP 9 High latitude Net Primary Production
HypZ 10 Hypoxic Zones
MC 11 Microbial Concepts
OAE 12 Ocean Acidification Effects
OCLTT 13 Oxygen and Capacity Limited Thermal Tolerance
SE 14 Synergistic Effects
SR 15 Species Richness (fish)
TE 16 Temperature Effects
Confidence in Attribution
Confidence in Detection
Confidence in Projection
Very low
Low
Medium
High
Very high

Figure 6-16

Figure 6-16: Overview of the levels of confidence in detection (left), as well as in projection (right) of climate change effects on ocean systems, in relation to the levels of confidence in attributing these effects to the respective climate forcings. Some climate change impacts have been condensed into rather broad categories in order not to overpopulate the figure (e.g. **BG**, **B**io-**G**eochemical Processes). Note that the term attribution is not only used in the context of detections but also for projections. Projections include both qualitative and quantitative extrapolations and simulations from fundamental principles and models. Experiments (field, laboratory and modeling) simulating future conditions may enhance the respective confidence levels above those for detection which refers to present day observations in the field. The empirical observations resulting from those experiments are then attributable to the respective drivers. Confidence rises further if these experiments identify the affected mechanisms and their response to future conditions. See text for further discussion of the depicted examples and categories. Confidence assignments focus on the nature and size of effects, not on the capacity of models to reliably quantify their magnitude.

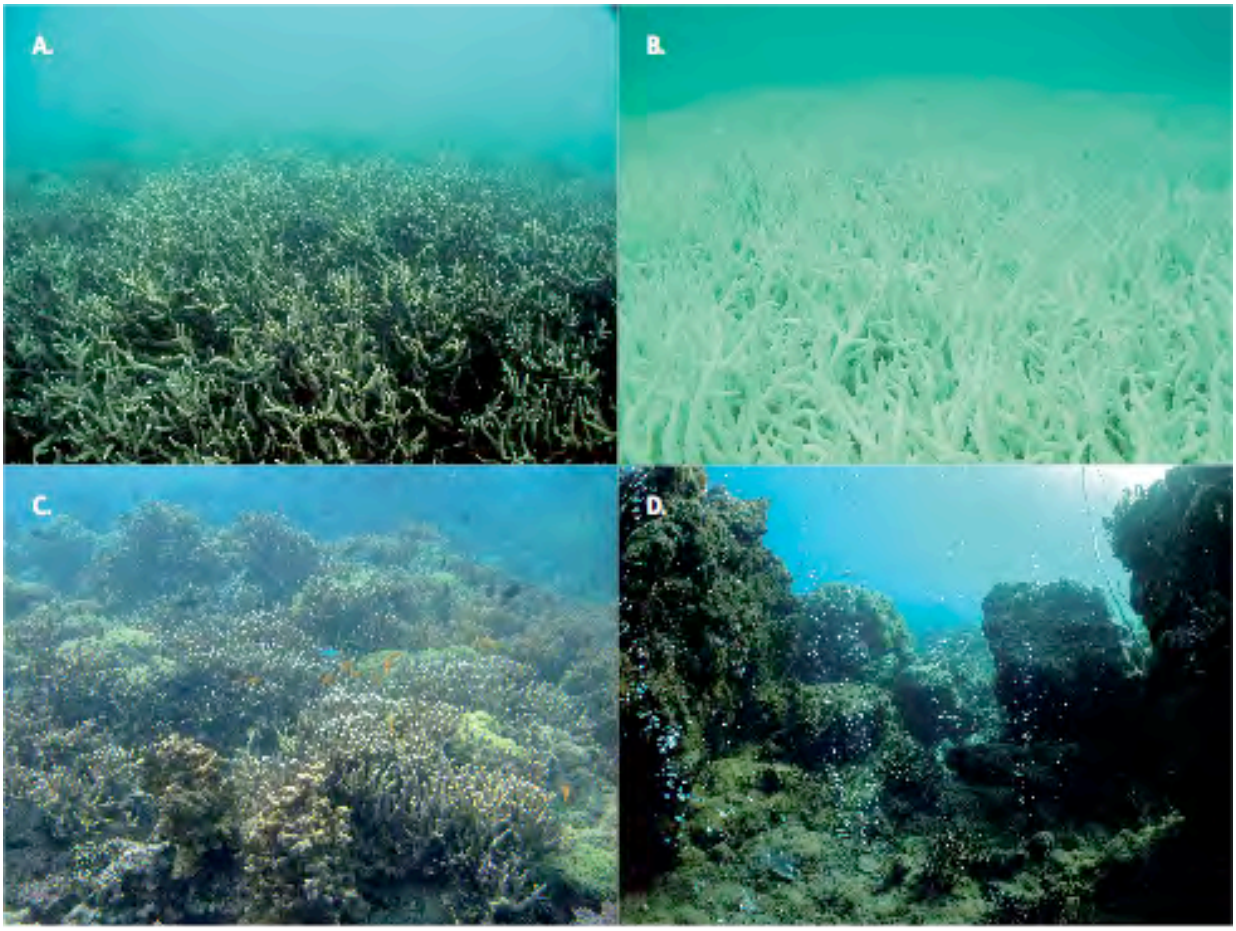

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

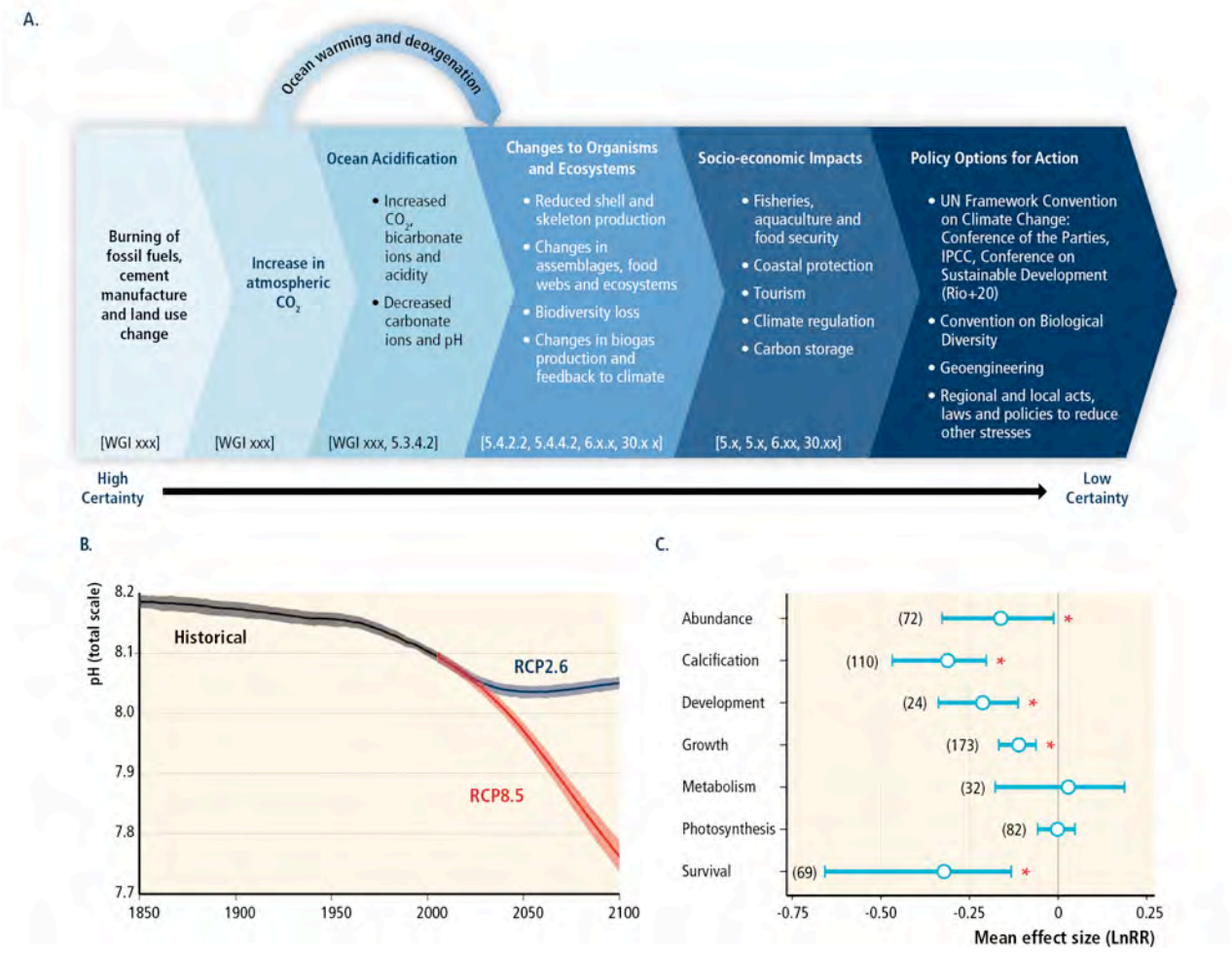

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

Chapter 7. Food Security and Food Production Systems

Coordinating Lead Authors
John R. Porter (Denmark), Liyong Xie (China)

Lead Authors
Andrew Challinor (UK), Kevern Cochrane (FAO), Mark Howden (Australia), Muhammad Mohsin Iqbal (Pakistan), David Lobell (USA), Maria Isabel Travasso (Argentina)

Contributing Authors
Netra Chhetri (Australia), Karen Garrett (USA), John Ingram (UK), Leslie Lipper (Italy), Nancy McCarthy (USA), Justin McGrath (USA), Daniel Smith (UK), Philip Thornton (UK), James Watson (UK), Lewis Ziska (USA)

Review Editors
Pramod Aggarwal (India), Kaija Hakala (Finland)

Volunteer Chapter Scientist
Joanne Jordan (UK)

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CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

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Executive Summary

The effects of climate change on food production are already evident in several regions of the world (*medium evidence, high agreement*). Negative impacts of climate trends have been more common than positive ones, although the latter predominate at high latitudes (*high confidence*). Since AR4, there have been several periods of rapid food price increases, demonstrating the partial sensitivity of current markets to climate variability. The role of climate change in these recent price changes is poorly understood, but *likely* small relative to other factors (*medium evidence, high agreement*). Social and economic issues such as energy policy and changes in household income will remain the main drivers of changes in food security in the near-term, regionally and locally. [7.2, Figures 7-2/3/4, Table 7-1]

By mid-century, when the global population will reach about nine billion people, many elements of the food system will be adversely affected by changes in climate (*high confidence*). Thereafter, and with *robust evidence and high agreement,* the human food system at scales from the local to global and particularly in low-latitude lands will be seriously and negatively affected by projected climate change from the mid-21st century onwards. [7.1, 7.2, 7.4] Global arable area is likely to increase from 2007 to 2050 (*medium evidence, high agreement*), with projected increases over this period of between 9% and 25% (*medium evidence, medium agreement*). When the effects of global warming are included, estimates range from a 20% increase in cropping area to a decline of 9% but with large regional differences (*limited evidence, low agreement*). [7.4.1]

Under scenarios of high levels of warming, leading to global mean temperatures of 4-6 ºC or higher above pre-industrial levels, extrapolation from current models suggests that the global risk to food production and security becomes very severe (*medium evidence, high agreement*). Such risks could affect ca. 90% of the global population based on the human population at that time and its demographic distribution (*medium evidence, low agreement*). These effects will be additively compounded by other factors such as the rise in tropospheric ozone

levels (*medium evidence, medium agreement*) and competition for water resources as between agriculture, food systems and other sectors of the economy. [7-4, Figure 7-5]

Long term climate changes are impacting the abundance and distribution of harvested aquatic species, both freshwater and marine, and aquaculture production systems in different parts of the world. [7.2.1.2, 7.3.2.6, 7.4.2] These are expected to continue with negative impacts on nutrition and food security for especially vulnerable people in some regions but with benefits in other regions which become more favourable for aquatic food production (*medium evidence, high agreement*). [7.5.1.1.3]

There is new understanding since AR4 of the sensitivity of crops to extreme heat, which reinforces the importance of temperature changes for determining impacts of climate change on crop yield at regional scales (*medium evidence, medium agreement*). At scales of individual countries or smaller, differences in precipitation projections continue to be an important source of uncertainty in future impacts (*medium evidence, high agreement*). [7.3]

Extreme heat also a negative effect on food quality in terms of nutrition and processing (*robust evidence, high agreement*). Impacts of increased heat stress and more frequent extreme events will be negative in all regions for livestock (*robust evidence, high agreement*); changes in animal diseases and vectors are less certain (*medium evidence, medium agreement*). Extreme climatic events, defined as extremely high and low temperatures and droughts and floods, are important for all food and fodder production, but particularly for annual determinate crops in which yield is harvested as seeds *(medium evidence, medium agreement)*. [7.3.2]

Evidence since AR4 confirms the positive effects of CO_2 and negative effects of elevated tropospheric ozone on crop yields (*high confidence*). There is emerging experimental and modelling evidence (*medium evidence, high agreement*) that interactions between production factors such as CO_2 and ozone, mean temperature, extremes, water and nitrogen can alter primary food production in complex ways. In concert with experimental results, the chapter results take more account of model and other uncertainties than has been the case previously. The large number of studies on mean crop yield impacts of changes in climate and CO_2 allow more robust statements than previously possible, but less confidence is given to simulated increases in yield variability (*medium evidence, medium agreement*). [7.3, Figures 7-5/7]

Changes in climate and CO_2 levels will enhance the distribution and increase the competiveness of agronomically important and invasive weeds (*robust evidence, high agreement*). Rising CO_2 reduces the effectiveness of herbicides (*medium evidence, high agreement*). The effects of climate change on disease pressure on food crops is uncertain, with evidence pointing to changed geographical ranges of diseases but less certain changes in disease intensity (*medium evidence, low agreement*). [7.3.2.1.2]

Without adaptation, moderate warming of up to 2ºC local temperatures are expected to reduce yields on average for the major cereals (wheat, rice and maize) in temperate regions, although many individual locations may benefit (*medium confidence*). There is confirmation that even modest warming up to 2ºC will decrease yields in low-latitude tropical regions (*robust evidence*, *medium agreement*). Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. From the 2070s onwards, all of the positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are very likely by this time and substantial, particularly for wheat (*robust evidence, high agreement*). [7-4, Figures 7-5/6/7]

Adaptation possibilities of food systems to climate change show a very wide range in effectiveness, with *medium confidence* that adaptation will increase in effectiveness with increasing local mean temperature up to ca. 3ºC local warming above pre-industrial, after which the net benefits no longer increase (*medium evidence, medium agreement*). Most studies however, have focussed on food production rather than on adapting food systems. Generally (*medium evidence, high agreement,*) adaptation leads to lower reductions in food production than in its absence with an overall crop yield difference in adaptation cases of about 15-20% over non-adaption cases, with more effective adaption at higher latitudes (*limited evidence, medium agreement,)* but with some adaptation options more effective than others. Thus, benefits of adaptation are greater for wheat, rice and maize in temperate rather than tropical regions. Key adaptations for fisheries are for policy and management to maintain ecosystems in

a state that is resilient to change, enabling occupational flexibility, and developing early warning systems for extreme events (*medium evidence, high agreement*). [7.5.1.1.3] Livestock systems' adaptations centre around adjusting management to the available resources, using breeds better adapted to the prevailing climate and removing barriers to adaptation such as improving credit access (*medium evidence, medium agreement*). A range of potential adaptation options exist across all food system activities, not just in the food production, but benefits from potential innovations in food processing, packaging, transport, storage and trade are insufficiently researched. [7.1, 7.5, 7.6, Figures 7-5/9]

In summary, the key messages from the synthesis and evaluation of the current evidence of the impacts of climate change on food security and food production systems and their adaptation are that:

- **The effects of climate change on food production systems and security are starting to be evident. [7.2]**
- **The combination of an extra two billion people who will require upwards of 50% more food by the mid-21st century in combination with predicted decreases in yields of the major cereals for global warming of more than *ca.* 2-3ºC, will put ever increasing pressure on the food system as a whole, even after taking account of calculated uncertainties. [7.1, 7.4]**
- **Adaptation is predicted to be partially effective in ameliorating the negative effects of warming. [7.5]**
- **Extremely high levels of warming (i.e., above 4°C increase in global mean temperature) will place immense pressure on global food security. [7.4]**
- **Climate changes impacts on the abundance and distribution of harvested aquatic species will affect the nutrition and food security for especially vulnerable peoples. [7.3, 7.4]**

7.1. Introduction and Context

Many definitions of food security exist. Maxwell and Slater (2003) noted over 200 as early as 1992 (Spring, 2009) and more have been formulated (Defra, 2006). While many of the earlier definitions centred on food production, the majority of more recent definitions promote the notion of access to food. The 1996 World Food Summit definition (FAO, 1996), which states that food security is met when "*all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life*", is still widely adopted. This definition puts the notion of access to food centre stage, also integrating dimensions of food availability, food utilisation and stability over time. The definition has a focus on the under-consumption of food whereas overconsumption and obesity are also relevant as factors in global public health.

While food security has been on the development agenda for decades, world-wide attention was given considerable impetus by the food 'price spike' in 2007-08, triggered by a complex set of long-term and short-term factors (von Braun and Torero, 2009). According to some estimates, the 'price spike' increased the number of hungry people by some 40 million (FAO, 2008) but other studies report a lower number (Headey and Fan, 2010). This link between food prices and numbers of food insecure people underscores the importance of the affordability of food in relation to food security. There is strong agreement that more than enough food is currently produced *per capita* to adequately feed the global population, yet about 870 million people remained hungry in 2012 (FAO, 2012), and millions more with insufficient nutrient (Pinstrup-Andersen, 2009). The two overriding questions for this chapter are how far climate change adds to current issues in food production systems and food security and the extent that it will do so in the future.

7.1.1. Summary from AR4

Food systems as integrated activities dealing with the impacts of climate change on the supply and demand for food did not feature strongly in AR4, where the strong emphasis was on food, fibre and forest production. Summary points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise crop and pasture yields. However, even slight warming will decrease yields in low-latitude regions. Extreme climate and weather events will, with *high confidence*, reduce food production with or without changes in mean conditions. The benefits of adaptation in crops such as changing varieties and/or planting times and other managements enable

avoidance of a 10-15% reduction in yield corresponding to 1-2°C local temperature increase. Adaptive capacity will be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish species are expected with *high confidence* at the edges of their ranges and any slowing in the meridional overturning circulation will have serious negative impacts on fisheries with a *medium confidence* level.

7.1.2. Food Systems

A food system includes all processes and infrastructure involved in satisfying a population's food security. It relates to the *Activities* of gathering/catching, growing, harvesting, storing, processing, packaging, transporting, marketing, consuming food, and disposing of food waste and food-related items (the 'food chain'). It also includes the food security *Outcomes* of these *Activities* related to availability and utilization of, and access to, food as well as those related to other socioeconomic and environmental factors. Drawing together the extensive (yet relatively distinct) literatures built up by the food chain and food security communities, respectively, a revised 'food systems' model has been formalised (Ericksen, 2008; Ericksen *et al*., 2010; Ingram, 2011). This model recognises that food systems operate within, are influenced by, and feed back to social, political, economic and environmental contexts (Figure 7-1).

[INSERT FIGURE 7-1 HERE
Figure 7-1: Main global environmental change (GEC) and socioeconomic drivers of food systems, the main food system activities, and the outcomes of these activities. The figure also shows the three main components of food security (circles), all of which need to be stable over time: Availability (with elements of production, distribution and trade); Access (affordability, allocation and preference); and Utilisation (nutritional value, cultural value and safety).]

There is good agreement that the impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socio-economic conditions (Vermeulen *et al*., 2012). Changes in food system activities give rise to changes in food security outcomes, *(medium evidence, high agreement)* but often researchers only consider the impacts on the food production element of food security. Food security needs consideration of how any intervention (i.e. a change in the food system activities) will also affect all other components of the food security outcomes; in principle, any intervention, even if only targeted at only one component (e.g. availability) will affect all three components due to the dynamic interactions between them, either directly or mediated via the feedback loops in Figure 7-1. Efforts to increase food production are nevertheless increasingly important as 50% more food will be needed by 2030 given current food consumption trends and assuming no significant reduction in food waste (FAO, 2010a).

7.1.3. The Current State of Food Security

There were an estimated 870 million people undernourished during the period 2010-2012, approximately 12.5% of the global population (FAO *et al*., 2012); thus, the vast majority of people currently have sufficient food. The vast majority of the undernourished (852 million) live in developing countries *(medium evidence, medium agreement).* Typically this is estimated based on aggregate national calorie availability and assumptions about food distribution and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show higher incidence of food insecurity than estimated by FAO. Smith *et al*., (2006) estimated average food insecurity rates of 59% for 12 African countries, compared to 39% estimate from FAO for the same period.

While there is *medium evidence, medium agreement* on absolute numbers, there is *robust evidence*, *high agreement* that Sub-Saharan Africa has the highest proportion of food insecure people; with up to 60% of people consuming insufficient calories for an active life. The largest numbers of food insecure are found in South Asia, which has roughly 300 million undernourished (FAO *et al*., 2012). In addition to common measures of calorie availability, food security can be broadened to include nutritional aspects based on the diversity of diet including not only staple foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). There is *robust evidence* and

high agreement that lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of additional (Lopez *et al*., 2006; Pinstrup-Andersen, 2009).

Food insecurity is closely tied to poverty, and more detailed surveys on poverty provide insight into where the food insecure live. Globally, about 25 to 30 percent of poor people – measured using either a $1 or $2 per day standard - live in urban areas (Ravallion *et al*., 2007; IFAD 2010). This is partly because most poor countries have a greater fraction of people living in rural areas, but also because poverty rates tend to be higher in rural settings (by slight margins in South Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to urban areas, with roughly two-thirds of the poor found in urban areas, a number that has been growing in the past decade *(medium evidence, medium agreement)*. The urban share of poverty has also been rising in other regions, although more slowly. It is expected that rural areas will continue to have the majority of poor people for at least the next few decades, even as population growth is higher in urban areas *(medium evidence, medium agreement)* (Ravallion *et al*., 2007; IFAD 2010).

For urban poor, who produce relatively small amounts of food, increases in food prices generally reduce food security. Since most rural poor produce some portion of the food they consume, the picture is more complicated. Much of the poor's income is from agricultural activities, which stands to benefit if prices rise. As mentioned, however, the rural poor still tend to be net consumers or marginal net producers. That is, they consume nearly all of what they grow and still need to buy additional food. If prices are rising more quickly for crops they grow, they can sell those and buy cheaper calories, resulting in a net increase in well-being. Rural wage rates may also increase in response to higher prices (for example, if workers are paid with a set amount of grain), with benefits for the many who earn part of their income from working other lands. Thus, the long-term welfare effects of price rises on rural poor are complex, and can vary depending on local factors.

The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid shifts make it difficult for the poor to adjust their activities to favour producing higher value items. Second, increased volatility leads to greater uncertainty about the future, and can dampen willingness to invest scarce resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of governments. Several factors have been found to contribute to increased price volatility: poorly articulated local markets, increased incidence of adverse weather events and greater reliance on production areas with high exposure to such risks, biofuel mandates, and increased links between energy and agricultural markets (World Bank, 2012). In some cases, trade interventions intended to reduce domestic food price volatility (e.g. export bans) had adverse effects both in local and global markets (HLPE, 2011; World Bank, 2012). Vulnerability to food price volatility depends on the degree to which households and countries are net food purchasers, the level of integration into global, regional and local markets and their relative degree of volatility, which in turn is conditional upon their respective governance (HLPE, 2011; World Bank, 2012) with *robust evidence* and *medium agreement*.

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

Food production systems have changed substantially over the past few decades. These changes were primarily the result of factors other than atmospheric CO_2 or climate, such as cultivar improvement and increased use of synthetic fertilizers, herbicides and irrigation. In many contexts the effects of past changes in weather or CO_2 level are viewed as noise that obscures the effects of agronomic or genetic changes. Yet understanding the effect of past CO_2 and climate shifts are a useful precursor to assessing future impacts and adaptation needs.

The number and strength of non-climate drivers of food systems and food security make formal detection and attribution of impacts extremely difficult. Most of these confounding factors, such as fertilizer use or adoption of modern hybrids in the case of crops, are not very well characterized in terms of spatial and temporal distributions, and the relationships between these factors and specific outcomes of interest (e.g., crop production) are often difficult to quantify. Attribution in other food production sectors is equally difficult. No studies to our knowledge simulate historical trends in food-related outcomes with and without changes in anthropogenic emissions of

greenhouse gases. A possible exception (Auffhammer *et al*., 2006) compared rice yield predictions in India using climate model simulations of temperature in the late 20th century with yields using observed temperatures for 1930-1960, the latter period used as a surrogate for climate without changes in greenhouse gases after 1960. In their study, they find rice yields would have been significantly higher without greenhouse gas emissions, thus attributing negative impacts to emissions but with *limited evidence*.

Attributions of crop changes are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behaviour. In most cases, models implicitly assume that farming practices or technologies did not adjust in response to climate over the period of interest. This assumption can be defended in some cases based on ancillary data on practices, or based on small differences between using models with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship between climate conditions and crop production has been shown to change over time because of management changes (Zhang *et al*., 2008; Liu *et al*., 2009; Sakurai *et al*., 2012).

7.2.1.1. Crop Production

Many studies of cropping systems have estimated impacts of observed changes in climate over the past few decades. Based on these studies, there is *medium confidence* (*medium evidence, high agreement*) that climate trends have negatively affected wheat and maize production for many regions, as well as *medium confidence* (*medium evidence, high agreement,*) for negative impacts on global aggregate production of these crops (Figure 7-2). There is also medium confidence (*medium evidence, high agreement*) that effects on rice and soybean yields have been small in major production regions and globally (Figure 7-2). There is also *high confidence* (*robust evidence*, *high agreement)* that warming has benefitted crop production in some cold regions, such as Northeast China or the United Kingdom (Jaggard *et al*., 2007; Supit et al., 2010; Chen *et al*., 2011; Gregory and Marshall, 2012).

[INSERT FIGURE 7-2 HERE
Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends (see 7.3.2.1.2) but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by temperate vs. tropical regions, modelling approach (process-based vs. statistical), whether CO2 effects were included, and crop. Studies were for China (Tao *et al*., 2006; Tao *et al*., 2008; Wang *et al*., 2008; You *et al*., 2009; Chen *et al*., 2010; Tao *et al*., 2012), India (Pathak *et al*., 2003; Auffhammer *et al*., 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell *et al*., 2005), France (Brisson *et al*., 2010), Scotland (Gregory and Marshall, 2012) Australia (Ludwig *et al*., 2009), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al*., 2010; Lobell *et al*., 2011). Values from all studies were converted to percentage yield change per decade.]

A sizable fraction of crop modelling studies were concerned with production for individual sites or provinces, scales below which the changes in climate conditions are attributable to anthropogenic activity (IPCC 2013, WG1, Chapter 10). Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution studies for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You *et al*., 2009; Lobell *et al*., 2011), at which trends in several climatic variables, including average summer temperatures, have been attributed to anthropogenic activity (IPCC 2013, WG1, Chapter 10). In particular, global temperature trends over the past few decades are attributable to human activity (IPCC, 2013, WG1, Chapter 10), and the studies discussed above indicate that this warming has had significant impacts on global yield trends of some crops.

Figure 7-3 presents a summary of the detectability of changes in growing season conditions (as measured by total degree-days during summer) and crop yield changes, as well as the ability to attribute changes to climate and CO_2 trends (in the case of yield changes) or anthropogenic emissions (in the case of growing season climate changes). As discussed above, attribution of yield impacts relies on multi-step attribution based on process understanding and observed climate trends. Also illustrated in Figure 7-3 is the fact that not all major cropping regions have

experienced significant climate trends in the past few decades, with the United States (in the lower, left-hand corner) the most notable example.

[INSERT FIGURE 7-3 HERE
Figure 7-3: Confidence in detection and attribution of observed impacts on crop yields and growing season degree days. Yield impacts include both direct climate effects and effects of elevated CO_2, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010). Negative yield impacts: 1= Global maize , 2= Global wheat, 3= South Asia wheat; 4 = China maize and wheat; Positive yield impacts: 5 = UK wheat, sugarbeet, and potato. Increase in growing degree days: 6 = South Asia, main crops; 7 = China, main crops; 8 = Europe, main crops; 9 = Latin America, main crops; 10 = North America, maize and soybean. Yield impact confidence based on studies listed in Figure 7-2. Growing degree day confidence based on detection and attribution of trends in growing season temperatures (IPCC 2013, WG1, Chapter 10).]

In general, little work in food production or food security research has focused on formally attributing observed changes to anthropogenic influence on the climate system. However, as the field of climate detection and attribution proceeds to finer spatial and temporal scales, and as agricultural modelling studies expand to broader scales, there should be many opportunities to link climate and crop studies in the next few years. Importantly, climate attribution is increasingly documented not only for measures of average conditions over growing seasons, but also for extremes. For instance, (Min *et al.*, 2011) attribute changes in rainfall extremes to anthropogenic activity, and these are widely acknowledged as important to cropping systems (Rosenzweig *et al.*, 2002). Frost damage is an important constraint on crop growth in many crops, including for various high-value crops, and significant reductions in frost occurrence have been observed and attributed to greenhouse gas emissions in nearly every region of the world (Alexander *et al.*, 2006; Zwiers *et al.*, 2011; IPCC, 2012). Positive trends in the occurrence of unusually hot nights are also attributable to human activity in most regions (Perring *et al.*, 2010, IPCC 2013, WG1, Chapter 10). These events are damaging to most crops, an effect that has been observed most commonly for rice yields (Peng *et al.*, 2004; Wassmann *et al.*, 2009; Welch *et al.*, 2010) as well as rice quality (Okada et al. 2011). Extremely high daytime temperatures are also damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009), and trends at the global scale in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Zwiers *et al.*, 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to greenhouse gas emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis *et al.*, 2005; Lobell *et al.*, 2007; Zwiers *et al.*, 2011).

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. It is *virtually certain* that the increase of atmospheric CO_2 by over 100 ppm since pre-industrial times has enhanced water use efficiency and yields, especially for C_3 crops, although these benefits played a minor role in driving overall yield trends (Amthor, 2001; Long *et al.*, 2006; McGrath and Lobell, 2011). As described earlier, increases in carbon dioxide are expected to have had negative impacts on carbon accretion in coral reefs with potential consequences for associated ecosystems and dependent social and economic activities (Hoegh-Guldberg *et al.*, 2007).

Emissions of CO_2 have also been associated with ozone (O_3) precursors that have driven a rise in tropospheric O_3 that harms crop yields (Morgan *et al.*, 2006; Mills *et al.*, 2007; *Section 7.3.2.1.2*). It is *very likely* that elevated O_3 since pre-industrial times has suppressed global production of major crops compared to what they would have been without O_3 increases, with estimated losses of roughly 10% for wheat and soybean and 3-5% for maize and rice (van Dingenen *et al.*, 2009). Impacts are most severe over India and China, but are also evident for soybean and maize in the United States (Fishman *et al.*, 2010; Boone et al. 2013).

7.2.1.2. Fisheries Production

The detection and attribution of impacts are as confounded in inland and marine fisheries as in terrestrial food production systems. Overfishing, habitat modification, pollution and inter-annual to decadal climate variability can all have impacts that are difficult to separate from those directly attributable to climate change. One of the best

studied areas is the North East Atlantic, where the temperature has increased rapidly in recent decades, associated with a poleward shift in distribution of fish (Perry *et al*., 2005; Brander, 2007; Cheung *et al*., 2010; *robust evidence, high agreement*). In the North Sea, within the NE Atlantic, the average species richness in the region, as indicated by the number of species recorded per year increased by approximately 33% between 1985 and 2006, a period during which North Sea bottom temperatures also rose significantly (Hiddink and Hofstede, 2008); inferring that the increase in richness has been related to the rising water temperature. These trends will have mixed implications for fisheries and aquaculture with some commercial species negatively and others positively affected (Cook and Heath, 2005). There is a similar well-documented example in the oceans off SE Australia with large warming trends associated with more southwards incursion of the Eastern Australian Current. This has resulted in southward migration of marine species into the oceans around eastern Tasmania with consequent impacts on ecosystem dynamics (Last *et al*., 2011; *robust evidence, high agreement*).

Coral reef ecosystems are important sources of fish for food for local inhabitants. More than 60% of coral reefs are considered to be under immediate threat of damage from a range of local threats, of which overfishing is the most serious followed by coastal development and pollution. The percentage under threat rises to 75% when the effect of rising ocean temperatures is added to these local impacts (Burke *et al*., 2011). There have been ongoing incidences of coral bleaching from rising sea temperatures since the 1970s which have already caused a global decline in coral reef cover and the trend is expected to continue as temperatures continue to rise (Munday *et al*., 2008; Chapter 30.6.1.1.2). Ocean acidification presents an additional threat by reducing carbon accretion (see Box 5-3 for further information). Wilson et al. (Wilson *et al*., 2006) demonstrated that declines in coral reef cover typically led to declines in abundance of the majority of fish species associated with coral reefs, with species that depended on live coral for food and shelter most impacted while some species that fed on invertebrates, algae or detritus increased.

There is considerably less information available on climate change impacts on fisheries and fishery resources in freshwater systems. (Xenopoulus *et al*., 2005) investigated the effect of climate change and water withdrawal on freshwater fish extinctions under the assumptions of two scenarios which they reported were consistent with IPCC SRES scenarios A2 and B2. They forecast that discharge would increase in between 65 and 70% of river basins in the world but it would decrease by as much as 80% in 133 rivers for which fish species data were available. In the rivers experiencing reduced discharge, by 2070 up to 75% of the local fish biodiversity would be 'headed toward extinction' because of changes in climate and water consumption. The areas where the highest rates of fish extinctions were forecast tended to be in tropical and subtropical areas. The authors concluded that climate change, through increased evapotranspiration and reduced precipitation, would be the most important cause of this loss under the two SRES scenarios with water consumption making a considerably smaller contribution. Rates of extinction in fish species cannot be directly related to changes in fishery production but their results indicate that there will be changes in riverine fish communities and productivity which will impact on fisheries, with negative impacts more probable in tropical and sub-tropical systems (*limited evidence; low agreement*).

Considerable attention has been given to the impacts of climate change in some African lakes but with mixed interpretations (see also Chapter 22.3.3.1.4.). For inland fisheries, there is evidence that increasing temperature has reduced the primary productivity of Lake Tanganyika in East Africa by increasing the stability of the water column and thereby reducing upwelling of nutrients into surface waters. The study by O'Reilly et al. (2003) estimated that this would have led to a decrease of approximately 30% in fish yields. However, Sarvala et al. (2006) disagreed and concluded that observed decreases in the fish catches could be explained by changed fishery practices. There has been a similar difference of opinion for Lake Kariba where Ndebele-Murisa et al., (2011) argued that a reduction in fisheries productivity had been caused by climate change while Marshall (Marshall, 2012) argues that the declines in fish catches experienced there can only have been caused by fishing. The Sahel region in northern Africa has historically demonstrated high variability. It experienced good rainfall in the 1960s, followed by severe drought over the next 7 years and below average precipitation from then until 2007. This dry period resulted in the area of Lake Chad decreasing from 26,000 km^2 in the 1960s to 1,425 km^2 in 2003. The decreasing area was associated with a decline in reported fish catches in Chad from over 100,000t in the late 1960s to under 70,000t in the early 1990s although there is considerable doubt about the accuracy of the reported catch figures, including up to the present (Welcomme, 2011; *medium evidence, low agreement*).

7.2.1.3. Livestock Production

In comparison to crop production, considerably less work has been published on observed impacts for non-crop food production systems, such as livestock and fisheries, and to our knowledge nothing has been published for hunting or collection of wild foods. A study of blue-tongue virus, an important ruminant disease, evaluated the effects of past and future climate trends on transmission risk, and concluded that climate changes have facilitated the recent and rapid spread of the virus into Europe (Guis et al. 2012).

7.2.2. Food Security

Food production is an important aspect of food security (Section 7.1), and the evidence that climate change has affected food production implies some effect on food security. Yet quantifying this effect is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine food security. There is thus limited direct evidence that unambiguously links climate change to impacts on food security.

One important aspect of food security is global food prices (Section 7.1.3). Although food prices gradually declined for most of the 20th century, since AR4 there have been several periods of rapid increases in international food prices (Figure 7-4). A major factor in recent price changes has been increased crop demand, notably via increased use in biofuel production related both to energy policy mandates and oil price fluctuations (Roberts and Schlenker, 2010; Wright, 2011; Mueller et al. 2011; Abbot et al. 2011). Yet fluctuations and trends in food production are also widely believed to have played a role in he recent price changes, as illustrated in Figure 7-4. Spikes in prices do not always follow weather induced shortfalls in supply, as illustrated by the lack of response to several events in the 1990's. However, price effects are especially likely in years with low stocks, which can result from sustained periods of low supply growth relative to demand. Domestic policy reactions can also amplify international price responses to weather events, as was the case with export bans announced by several countries since 2007 (FAO, 2008). In a study of global production responses to climate trends, (Lobell *et al*., 2011) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO_2 over the study period were considered. Since the price models were developed for a period ending in 2003, these estimates do not account for the policy responses witnessed in recent years which have amplified the price responses to weather.

[INSERT FIGURE 7-4 HERE
Figure 7-4: Since the AR4 report, food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index, along with events when a top 5 producer of a crop had yields 25% below trend line (indicative of a big weather effect). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years, perhaps reflecting the importance of interactions with global storage levels and rapid growth in crop demand. At the same time, because of increased biofuel demand, food prices are also increasingly linked to the price of crude oil, shown in the blue line (data available at http://www.eia.gov). Therefore, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002-2004 averages.]

7.3. Assessing Impacts, Vulnerabilities, and Risks

7.3.1. Methods and Associated Uncertainties

7.3.1.1. Assessing Impacts

Methods developed or extended since AR4 have resulted in more robust statements on climate impacts through:

- Improved quantification and presentation of uncertainty. Descriptions of processes and trade-offs, and expression of uncertainty in the temporal dimension, are two methods that have been shown to be more effective that presentation of uncertainty in the outcome variable (e.g. yield).

- Greater use of historical empirical evidence of the relationship between climate and food production.

The methods used for field and controlled environment experiments remain similar to those at the time of AR4. There has been a greater interest in the use of Remote Sensing (RS)/Geographic information System (GIS) techniques for assessing temporal and spatial changes in land use particularly in agricultural land use for assessment of food security status (Fishman *et al.*, 2010). There has also been an increase in the number of Free Air Concentration Enrichment (FACE) studies that examine ozone instead of, or in addition to, carbon dioxide. A number of meta-analyses of experimental studies, in particular (FACE) studies have been made since AR4. However, debate continues on the disparities between results from FACE experiments and non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to show lower elevated CO_2 responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct, others have argued that the results are only similar when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth *et al.*, 2008). Hence comparisons between different methodologies must take care to control for differences in water levels. Another reason for differences between experiments may be differences in the temporal variance of CO_2 – i.e. whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the number of FACE studies are still quite low, which limits statistical power when evaluating the average yield effects of elevated CO_2 or interactions with temperature and moisture (*Section 7.3.2*).

Numerical simulation models can be used to investigate a larger number of possible environmental and management conditions than physical experiments. This, in turn, enables a broader range of statements regarding the response of food production systems to climate variability and change. Previous assessment reports have documented new knowledge resulting from numerical simulation of the response of food production to climate change. AR4 noted the increasing number of regional studies, which is a trend that has continued to date (Challinor *et al.*, 2009). Since AR4, crop models have been used to examine a large number of management and environmental conditions, such as interactions among various components of food production systems (Lenz-Wiedemann *et al.*, 2010), determination of optimum crop management practices (Soltani and Hoogenboom, 2007), vulnerability and adaptability assessments (Humaira *et al.*, 2009), evaluation of water consumption and water use efficiency (Mo *et al.*, 2009; Kang *et al.*, 2009), estimation of changes and uncertainties (Bellocchi *et al.*, 2010) and fostering communication between scientists, managers, policymakers and planners (*robust evidence; medium agreement*).

Novel developments since AR4 in the methodologies used for modelling since include more work that quantifies uncertainty in both climate and its impacts, particularly for crops, and models that include crop growth as part of broader land surface and earth systems models (e.g. (Bondeau *et al.*, 2007; Osborne *et al.*, 2007). Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Baysian methods to constrain crop model parameters (Iizumi *et al.*, 2009; Tao *et al.*, 2009a). It is also increasingly common to assess both bio-physical and socio-economic drivers of crop productivity within the same study (Fraser *et al.*, 2008; Reidsma *et al.*, 2009; Tao *et al.*, 2009b; Challinor *et al.*, 2010). Finally, an important recent development is the systematic comparison of results from different modelling and experimental approaches for providing insights into model uncertainties as well as to develop risk management (Challinor and Wheeler, 2008; Kang *et al.*, 2009; Schlenker and David, 2010; Rosenzweig *et al.*, 2013).

Increased quantification of uncertainty can lead to clear statements regarding climate impacts. Studies with different methods have been shown to produce convergent results for some crops and locations (Challinor *et al.*, 2009; *medium evidence, medium agreement*). The methods used to describe uncertainty have also improved since AR4. The projected range of global and local temperature changes can be described by quantifying uncertainty in the temporal dimension, rather than that in temperature itself (Joshi *et al.*, 2011), and a similar approach can be used for crop yield (Figure 7-5). Descriptions of uncertainty that present key processes and trade-offs, rather than ranges of outcome variables, have also proved to be useful tools for understanding future impacts (Thornton *et al.*, 2009; Hawkins *et al.*, 2012; Ruane *et al.*, 2013).

A considerable body of work since AR4 has used extensive datasets of country- , regional- and farm- level crop yield together with observed and/or simulated weather time series in order to assess the sensitivity of food production to weather and climate. These statistical models offer a complement to more process-based model

approaches, some of which require many assumptions about soil and management practices. The regional-scale statistical models that have been developed in recent years can thus produce more widely applicable results than field and controlled environment experiments, whilst avoiding the need for assumptions regarding management and planting dates. Although statistical models forfeit some of the process knowledge embedded in other approaches, they can often reproduce the behavior of other models (Iglesias *et al*., 2000; Lobell and Burke, 2010) and can leverage within one study a growing availability of crop and weather data (Welch *et al*., 2010; Lobell *et al*., 2011). Statistical models usually exclude the direct impact of elevated CO_2, making multi-decadal prediction problematic. Similarly, technological progress and its interaction with climatic variability are not simulated by statistical models. Regional-scale process-based models tend to include at least some of these processes. In determining future trends, crop models of all types can only extrapolate based on historically-determined relationships. Process-based models extrapolate based on measured interactions and mechanisms, whilst statistical models extrapolate based on empirically determined relationships. Agro-climatic indices provide another alternative to process-based crop models that avoid various assumptions by focusing on farmer-relevant metrics, rather than providing yield predictions *per se* (Trnka *et al*., 2011). However, correlations between climate, or associated indices, and yield are not always statistically significant.

The robustness of crop model results depends on data quality, model skill prediction and model complexity (Bellocchi *et al*., 2010). Modelling and experiments are each subject to their own uncertainties. Measurement uncertainty is a feature of field and controlled environment experiments. For example, interactions between CO_2 fertilisation, temperature, soil nutrients, ozone, pests and weeds is not well understood (Soussana *et al*., 2010) and therefore most crop models do not include all these effects, nor broader issues of water availability, such as competition for water between industry and households (Piao *et al*., 2010). There are also uncertainties associated with generalizing the results of field experiments, since each one has been conducted relatively few times under a relatively small range of environmental and management conditions, and for a limited number of genotypes. This limits breadth of applicability both through limited sample size and limited representation of the diversity of genotypic responses to environment (Craufurd *et al*., 2013). For example, yield increases normalised by increase in CO_2 have been found to vary between zero and over 30% among crop varieties (Tausz *et al*., 2011).

Models have the advantage of exploring a larger number of situations, but with less certainty in the determination of the response variable than in field studies. The uncertainty in climate simulation is generally larger than, or sometimes comparable to, the uncertainty in crop simulation using a single model (Iizumi *et al*., 2011).There is significant uncertainty in agricultural simulation arising from climate model error, and since AR4 the choice of method for GCM bias correction has been identified as a source of uncertainty, even in the absence of downscaling, which is comparable in some cases to that from scenarios and choice of GCM (Hawkins *et al*., 2012). There is also a contribution to uncertainty in crop model output from yield measurement error, through the calibration procedure. Yield measurements rarely have associated error bars to give an indication of accuracy. Greater access to accurate regional-scale crop yield data can lead to decreased uncertainty in projected yields

The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons have shown variations in yield and biomass of more than 100% (Palosuo et al., 2011).Early results from impacts studies with multiple crop models suggest that the crop model uncertainty can be larger than that caused by GCMs, due in particular to high temperature and temperature-by-CO_2 interactions (Asseng *et al*., 2013). Given these different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modeling lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts, vulnerabilities and risks. This approach to assessment is applied to each of the topics described in the rest of the chapter.

7.3.1.2. Treatment of Adaptation in Impacts Studies

Adaptation occurs on a range of timescales and by a range of actors. Incremental adaptation, such as a change in crop management, can occur relatively autonomously within farming systems. It is the type of adaptation most commonly assessed in the impacts literature, and it is the only form of adaptation discussed in sections 7.3 and 7.4. Systemic and transformational adaptations are discussed in section 7.5.

7.3.2. Sensitivity of Food Production to Weather and Climate

Since AR4, understanding of the impacts of a range of biophysical processes and associated outcomes has been improved:

- Heat stress effects have been better quantified at regional and local scales. There is no evidence that the response is uniform across spatial scale.
- AR4 states that water stressed crops may benefit more than well-watered crops from elevated CO2. Work since then suggests this may not consistently be the case.
- Evidence shows the greater importance of temperature over precipitation in determining regional-scale crop yields in some regions
- Impacts on crop yield as a function of local temperature change: AR4 confirmation that even slight warming will decrease yields in low-latitude regions (*medium confidence*) and that temperate wheat yield decreases are *about as likely as not* for moderate warming.

The majority of research into the sensitivity of food production to weather and climate remains focussed on crops. The majority of that work is focussed on impacts on the major annual crops such as maize, wheat and rice, a focus that is commensurate with the area harvested of these crops (White *et al*., 2011). Whilst there are many other crops of importance to food systems, the crops discussed here reflect both the availability of research and the global remit of this chapter.

7.3.2.1. Cereals, Oilseeds, and Legumes

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have widely been used since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature (Iqbal *et al*., 2009), decline in grain set when high temperatures occur during flowering (Moriondo *et al*., 2011), and increased water stress at high temperatures throughout the growing cycle (Lobell *et al*., 2013b). Temperatures responses are generally well-understood for temperatures up to the optimum temperature for development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as well understood (Craufurd and Wheeler, 2009). For example, temperatures above 34 °C after flowering appear to rapidly speed senescence in wheat (Lobell *et al*., 2013b; Asseng *et al*., 2013), but many crop models do not represent this process.

The overall relationship between weather and yields is often crop and region specific, depending on differences in baseline climate, management and soil, and the duration and timing of crop exposure to various conditions. For example, rice yields in China have been found to be positively correlated with temperature in some regions and negatively correlated in others (Zhang *et al*., 2010). This difference may be due to positive correlation between temperature and solar radiation in the former case, and negative correlation between temperature and water stress in the latter case. Similarly, although studies consistently show spikelet sterility in rice for daytime temperatures exceeding 33 °C (Jadadish et al., 2007; Wassmann *et al*., 2009), some statistical studies find a positive effect of daytime warming on yields because these extremes are not reached frequently enough to affect yields (Welch *et al*., 2010). Responses to temperature may vary according whether yields are limited by low or high temperatures. However, there is evidence that high temperatures will limit future yields even in cooler environments (Semenov et al., 2012; Teixeira *et al*., 2013).

In cool season legumes, the threshold for heat stress during the reproductive phase is above 25ºC (daily maximum temperature) and experimental results with field-pea in North India show that temperatures higher than 25ºC at the onset of the reproductive phase led to reductions in pod setting (30%), seeds per pod (41%) and seed weight (36%) and consequently total productivity decreased by 48% (Ali and Gupta, 2012). Also in North India chickpea yields during the last years decreased between 0.53 and 3 q. ha^{-1} per 1ºC increase in seasonal temperature (Kalra *et al*.,

2008).Even if chickpea is more heat tolerant than other cool season legumes, high temperatures (above 30ºC) during the reproductive phase can affect seed yield (Devasirvatham *et al*., 2012). Simulation results for short duration pigeon pea in Kenya projected decreases in yields between 7% and 28.7% with 1ºC and 5ºC increase in temperature respectively (Cooper *et al*., 2009).

The relative importance of temperature and water stress for crop productivity can be assessed using models, and can vary according to the criteria used for assessment (Challinor *et al*., 2010). There are also some cases where the sign of a correlation depends on the direction of the change. For example, (Thornton *et al*., 2009) found that the response crop yields to climate change in the drylands of East Africa is insensitive to rainfall, since wetter climates are associated with warmer temperatures that act to reduce yields. Variation in crop-climate relationships can also result from the analytical methods used and/or the spatial scale of the analysis e.g. (Challinor and Wheeler, 2008). For example, increases in daily maximum temperature have been found to increase the yield of rice at a number of sites across Asia (Welch *et al*., 2010), whilst negative responses due to spikelet sterility are a well-known phenomenon in controlled environment experiments. Crop models can be used to quantify abiotic stresses such as these (Challinor *et al*., 2009), although only by hypothesizing that the functional responses to weather derived from experiments are valid at regional scales. Thus, whilst many fundamental bio-physical processes are understood at the plant or field scale, it remains difficult to quantify the extent to which these mechanisms are responsible for the observed regional-scale relationships between crop yield and weather.

Since precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of precipitation tend to diminish as the spatial domain widens. As a result, precipitation becomes less important as a predictor of crop yields at broad scales (Lobell and Field, 2007; Li *et al*., 2010). Similarly, projected changes in precipitation from climate models tend to be more spatially variable than temperature, leading to the greater importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke, 2008). There is also evidence that where irrigation increases over time the influence of temperature on yields starts to dominate over that of precipitation (Hawkins *et al*., 2012)

A meta-analysis of yield impact studies for major cereals (Challinor *et al*., 2013), including both pre- and post- AR4 contributions, gave broadly similar results to AR4 and to a more recent meta-analysis using multiple impacts models (Frieler *et al*., 2013). Challinor *et al*. (2013) reported tropical and temperate regions separately: yields of maize, wheat and rice begin to decline with 1-2ºC of local warming in the tropics, with temperate maize yields being less clearly affected at these temperatures and moderately affected for greater warming (Figure 7-5). The new analysis confirms AR4 findings that even slight warming will decrease yields in low-latitude regions (*medium evidence, high agreement*). However, whilst AR4 had few indications of yield reductions at less than 2ºC of local warming, the new analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures. Hence, whilst AR4 concluded with *medium confidence* that in mid- to high-latitude regions moderate warming will raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for moderate warming. Quantitative assessments of yield changes can be found in section 7.4. Within both tropical and temperate regions regional variability, which cannot be summarised in meta-analyses, will be important in determining how climate change affects particular agricultural systems.

[INSERT FIGURE 7-5 HERE
Figure 7-5: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated according to the presence (blue) or absence (red) of adaptation. Note that 10 of the 1125 datapoints across all six panels are outside the yield change range shown. These were omitted for clarity.]

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further observational evidence since AR4 that response to a change in CO_2 depends on plant type; C_3 or C_4 (DaMatta *et al*., 2010). The effect of increase in CO_2 concentration tends to be higher in C_3 plants (e.g. wheat, rice, cotton, soybean, sugar beets, and potatoes) than in C_4 plants (e.g. corn, sorghum, sugarcane), because photosynthesis

rates in C_4 crops are less responsive to increases in ambient CO_2 (Leakey, 2009). The highest fertilization responses have been observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs (Fleisher *et al.*, 2008; Högy and Fangmeier, 2009).

FACE studies have shown that the impact of elevated CO_2 varies according to temperature and availability of water and nutrients; yet there is a strong geographical bias of FACE studies towards temperate zone (Leakey et al., 2013). Water-stressed crops are expected to respond more strongly to elevated CO_2 than well-watered crops, because of CO_2 induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems, and that rain-fed systems in drier regions or years will benefit more than in wetter conditions. This expectation has been cited in TAR and AR4, and new evidence based on historical observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher for dry years than for wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models and FACE meta-analyses and there is some suggestion that the relationship between water stress and assimilation may vary with spatial scale, with canopy analyses showing a reversal of the expected leaf-level dry vs wet signal (Challinor and Wheeler, 2008).

Ozone in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the troposphere it is a phytotoxic air pollutant. Global background concentration of ozone has increased since pre-industrial era due to anthropogenic emission of its precursor, by vehicles, power plants, biomass burning and other sources of combustion. Like CO_2, O_3 is taken up by green leaves through stomata during photosynthesis but unlike CO_2, its concentration is significantly variable depending on geographic location, elevation and extent of anthropogenic sources. Being a powerful oxidant, ozone and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions (Mills *et al.*, 2009; Ainsworth and McGrath, 2010). This results in stunted crop plants, inferior crop quality and decreased yields (Booker *et al.*, 2009; Fuhrer, 2009; Vandermeiren *et al.*, 2009; Pleijel and Uddling, 2012) and posing a growing threat to global food security (*robust evidence, high agreement*).

The literature published since AR4 further corroborates the negative impacts of increasing concentrations of surface ozone on yield losses on global (Van Dingenen *et al.*, 2009; Teixeira *et al.*, 2011; Avnery *et al.*, 2011a; Avnery *et al.*, 2011b) and regional level (Northern Hemisphere: Hollaway et al, (2011); USA: (Emberson *et al.*, 2009; Fuhrer, 2009; Fishman *et al.*, 2010); India (Roy *et al.*, 2009; Rai *et al.*, 2010; Sarkar and Agrawal, 2010); China: (Wang *et al.*, 2007; Piao *et al.*, 2010); Bangladesh: (Akhtar *et al.*, 2010); Europe: (Hayes *et al.*, 2007; Vandermeiren *et al.*, 2009; Fuhrer, 2009). The global yield losses of soybean, wheat and maize in 2000 ranged from 8-15% amounting to production losses of $11-18 billion (Avnery *et al.*, 2011a). The projected yield losses for the near future (year 2030) would be substantial but less severe under IPCC B2 scenario than A2; yield reduction under A2 would be 9-25% with production losses of $17-35 billion and under B1 scenario 9-17% with production losses of $12-21 billion (Avnery *et al.*, 2011b). In separate meta-analyses, some researchers reported even higher losses in wheat yield (Feng *et al.*, 2008) and high losses in rice yield (Ainsworth, 2008) at elevated ozone concentrations. These studies also pointed out the regional hotspots of East and South-east Asia and Eastern US, strong seasonality of O_3 formation (with peaks in pre- and post-monsoon months in India) depending on precursor emission and climate factors and role of crop management practices, such as cropping system, crop species (Teixeira *et al.*, 2013) and crop genotype (Feng *et al.*, 2011), (Biswas *et al.*, 2008; Zhu *et al.*, 2011). The sensitivity of crops to O_3 damage was in the order: soybean ≥ wheat > rice > maize. The irrigated crops suffered highest production losses. Ozone may have direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (Royal Society, 2008; *robust evidence, high agreement*).

The interactive effects of ozone with other environmental factors such as CO_2, temperature, moisture, light, are important but not well understood. Generally, the ambient and increasing concentrations of O_3 and CO_2 individually exert counteractive effects on C_3 plants (Tianhong *et al.*, 2005; Ainsworth, 2008; Gillespie *et al.*, 2012); but their interactive effect may compensate for each other (Ainsworth, 2008; Taub *et al.*, 2008; Gillespie *et al.*, 2012). In some studies, crops grown in both elevated CO_2 and O_3 concentrations showed yield losses which were less than with O_3 alone (Taub *et al.*, 2008; Fuhrer, 2009). The losses might also be greater when elevated O_3 combines with high temperature (Long, 2012) particularly during grain filling of wheat, when elevated ozone causes premature leaf senescence (Feng *et al.*, 2008; Feng *et al.*, 2011). Such interactions may be important for understanding ozone

tolerance in C_3 food crops and for exploiting rising CO_2 concentrations for yield enhancement (Ainsworth *et al.*, 2008; Mittler and Blumwald, 2010; Ziska *et al*., 2012). Periods of abundant radiation, high temperature and adequate water supply most favourable for agricultural production are also favourable for the formation of surface ozone; thus the effects of ozone on crops are often not visible in contrast to other yield reducing factors such as insect pests and diseases (Long, 2012).

7.3.2.2. Other Crops

Increases in temperature are already affecting phenology in perennial crops since the accumulation of winter chill hours is decreasing. Observed trends in winter chill range between -50 and -260 chill hours per decade in California and predicted rates of reduced winter chill, for the period between 1950 and 2100, are on the order of -40 h per decade (Baldocchi and Wong, 2008). Averaging over three GCMs annual winter chill loss by 2050 compared to 1970 would amount 17.7 % to 22.6 % in Egypt (Farag *et al*., 2010). The analysis made by (Wolfe *et al*., 2008) using HadCM3 projections under A1F1 and B1 scenarios indicate that some 400 h could be assured along the century, benefiting species with low chill requirement in the north-eastern USA.

Earlier flowering and maturity have been observed *(robust evidence, high agreement*) worldwide in grapes (García-Mozo *et al*., 2010; Duchêne *et al*., 2010; Jorquera-Fontena and Orrego-Verdugo, 2010; Sadras and Petrie, 2011; Webb *et al*., 2011), apples (Fujisawa and Koyabashi, 2010; Grab and Craparo, 2011) and other perennial horticultural crops (Sugiura *et al*., 2012; Glenn *et al*., 2013). Assessing climate change impacts on fruit production in California towards 2050, (Lobell and Field, 2011) found a slightly positive yield trend (*ca*. 5%) for almonds and negative trends for table grapes (5%), berries (10%) and cherries (20%) as compared to 2000. Also in eastern Washington in US under A1F1 and B1 scenarios without the effect of elevated CO2, future climate change is projected to decrease apple production by 1%, 3%, and 4% for 2020, 2040, and 2080 respectively, but when the effect of CO_2 is added, yields are projected to increase by 6% (2020s), 9% (2040s), and 16% (2080s) (Stöckle *et al*., 2010). Reductions in suitability for grapevine are expected in most of the wine producing regions (Hall and Jones, 2009; White *et al*., 2009; Jones *et al*., 2010). Grapes/wine production and quality will be affected in Europe, US, Australia
(Jones *et al*., 2005; Wolfe *et al*., 2008; Cozzolino *et al*., 2010), Chapter 25 WG2), although it could be a benefit in Portugal (Santos *et al*., 2011) and British Columbia in Canada (Rayne *et al*., 2009).

Important crops in Brazil like sugarcane and coffee are expected to migrate towards more favorable zones in the South (Pinto, 2007; Marin *et al*., 2009; Pinto et al., 2008; Chapter 27 WG2). Sugarcane fresh stalk mass is generally expected to gain from both warming and elevated CO2 in Brazil (Marin *et al*., 2013). The suitability for coffee crops in Costa Rica, Nicaragua and El Salvador will be reduced by 40% (Glenn *et al*., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops towards higher altitudes by mid-century (Ramirez-Villegas *et al*., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne, et al., 2007).

Cassava is an important source of food for many people in Africa and Latin America and recent studies suggest that future climate could not significantly affect its productivity as this crop is characterized by elevated optimum temperature for photosynthesis and growth, and a positive response to CO_2 increases (Jarvis *et al*., 2012; Rosenthal and Ort, 2012; El-Sharkawy, 2012).

The suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes towards 2100 (Schaefleitner *et al*., 2011). Projections for Europe indicate that by 2030 and 2050 the impacts on potato yields will be mostly positive but towards the end of the century negative impacts are expected in the overall continent except in some northern countries (Supit *et al*., 2012). In Eastern China yields are expected to increase in the North and to decrease in the South by 2100 (Chavas *et al*., 2009), also in the Peruvian Altiplano negative impacts are expected under A2 and B2 scenarios by 2100 (Sanabria and Lhomme, 2012) while in eastern Washington in US, potato yields could slightly decrease (-2/-3%) under A1F1 and B1 scenarios (Stöckle *et al*., 2010).

7.3.2.3. Pests, Weeds, Diseases

7.3.2.3.1. Sensitivity of pests, weeds, and diseases to weather and climate

As a world-wide average, current yield loss in major crop species due to animal pests and (non-virus) pathogens, in the absence of any physical, biological or chemical crop protection, is estimated at 18% and 16%, respectively (Oerke, 2006). Although physical changes associated with climate uncertainty are recognized and assessed, (e.g. drought, water, temperature) in the context of agricultural productivity, less attention has focused on biological interactions and climate, even though it is universally recognized that weeds, insects and diseases have limited crop yield potential. A fair question then is to ask whether such limitations will increase or decrease in response to future changes in CO_2/climate?

The effects of weather on important diseases and pests, including optimal temperature and moisture conditions, have been studied in detail for decades (De Wolf and Isard, 2007). This research forms a base for understanding that climate change will change potential losses to many pests and diseases. Changes in temperature can support range expansions through changes in winter and summer extremes, and thus the potential for overwintering or summer survival. CO2 and ozone can either increase or decrease plant disease, and can exhibit important interactions in effects, suggesting incorporation of these risk factors in analyses may need to be system specific (Chakraborty *et al*., 2008; Eastburn *et al*., 2011). It is challenging to estimate the extent to which observed changes in effects may be due to climate change because of the many factors that interact to result in pest and disease risk and management decisions (Chakraborty and Newton, 2011; Garrett *et al*., 2011). Interactions with landscape effects may be particularly important in such perennial agricultural systems as forests and grasslands (Pautasso *et al*., 2010).

The rarity of long-term studies of plant diseases and pests is a problem for the evaluation of climate change effects, but there are some examples of the potential for such analyses available. Studies of a wheat experiment at Rothamsted Research Station UK, maintained for over 160 years, have revealed shifts in foliar wheat pathogens linked to rainfall, temperature, and SO_2 emissions (Bearchell *et al*., 2005; Shaw *et al*., 2008). Wheat rust risk has been observed to respond to ENSO (Scherm and Yang, 1995). Over almost seven decades, earlier and more frequent epidemics of potato late blight, and more frequent pesticide use, were observed in Finland, associated with changing climate conditions and lack of crop rotation (Hannukkala *et al*., 2007). Up to a point, adaptation to climate change will be similar to adaptation to other new scenarios as agricultural systems have moved around the world (Coakley *et al*., 1999; Juroszek and von Tiedemann, 2011). As an example of the effect of climate on management efficacy, higher diversity potato systems designed for management of potato late blight had lower utility in climatic zones where potato growing seasons were longer and presumably there were higher regional pathogen loads (Garrett et al., 2009).

Changes in climate are expected to affect the range of specific species of insects and diseases for a given crop growing region. For example, Cannon (1998) has suggested that migratory insects could colonize crops over a larger range in response to temperature increases, with subsequent reductions in yield. Guitierrez (2000) has suggested that predator and insect herbivores are will respond differently to increasing temperature, with possible reductions in insect predation (i.e. greater insect numbers). While plant-pathogen interactions are recognised as a factor affecting crop yields, our ability to predict CO_2/climate change impacts on pathogen biology and subsequent changes on yield of rice, soybean, wheat inter alia is tenuous at best, because with few exceptions (Savary *et al*., 2011), experimental data are not available and analyses focus on individual diseases rather than the complete set of important diseases (*medium evidence, medium agreement*).

Ostensibly, since many agricultural weeds are C_4, and soybean, wheat and rice, C_3, increasing CO_2 should reduce crop losses due to weedy competition since the C_3 pathway, in general, shows a stronger response to rising carbon dioxide levels. However, the argument that rising CO_2 will reduce weedy competition because the C_4 photosynthetic pathway is over-represented among weed species (Holm, 1977) does not consider the range of available C_3 and C_4 weed species present within the agronomic seed bank. For example, in the United States, every crop, on average, competes with an assemblage of 8-10 weed species (Bridges, 1992). In addition, CO_2, and/or climate, can also affect weed demographics. For example, with field grown soybean, elevated CO_2 per se appeared to be a factor in increasing the relative proportion of C_3 to C_4 weedy species with subsequent reductions in soybean yields (Ziska and

Goins, 2006). For rice and barnyard grass (C_4), increasing CO_2 favored rice, but if both temperature and CO_2 increased simultaneously, the C_4 weed was favored, primarily because higher temperatures resulted in increased seed yield loss for rice (Alberto et al, 1996). Overall, rising atmospheric CO_2 can increase the extent of crop losses due to a greater response of the weed relative to the crop (Ziska, 2000; Ziska, 2003). If weeds are not managed such losses may exceed any observed stimulation in crop yield associated with elevated CO_2 (Ziska, 2000; Ziska, 2003). For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species, (often among the "worst" weeds in agronomic situations, e.g. rice and red rice) the decrease in seed yield from weeds may, in fact, be greater in response to increasing atmospheric CO_2 (Ziska, 2010). Climate change may be a factor in extending the northward migration of agronomic and invasive weeds (e.g. (Ziska *et al.*, 2011). The projected warming may be exceeding maximum rates of plant migration observed in post-glacial time periods (Malcolm *et al.*, 2002), resulting in preferential selection for the most mobile plant species. A number of characteristics associated with long-distance dispersal are commonly found among weeds (Rejmánek, 1996) suggesting that they will be among the fastest to migrate with increasing temperatures (Dukes and Mooney, 1999). In addition, climate (e.g. precipitation) and/or temperature may change the demographics of C_3 and C_4 weed species in crop production (e.g. (Ziska and Goins, 2006; McDonald *et al.*, 2009).

Initial studies indicate a potential decline in herbicide efficacy with rising CO_2 and/or temperature for some weeds (Ziska and Goins, 2006; Archambault, 2007; Manea *et al.*, 2011). For Canada thistle, increasing CO_2 appears to have induced greater below-ground growth of roots, diluting the active ingredient of the herbicide and making chemical control less effective (Ziska *et al.*, 2004). To date, studies on physical, cultural or biological weed control are lacking.

7.3.2.3.2. Effects of climate change on pests, weeds, and diseases

Climate change scenario analyses are available for some pests and diseases. For example, range expansion has been predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot *et al.*, 2004) and for phoma stem canker on oilseed rape in the UK (Evans *et al.*, 2008). Increased generations under climate change for the coffee nematode have been predicted for the coffee nematode in Brazil (Ghini *et al.*, 2008). Walnut pests in California are predicted to experience increased numbers of generations under climate change scenarios (Luedeling *et al.*, 2011). Potato late blight risk increases in some areas of the world, and decreases in others, under climate change scenarios (Sparks *et al.*, 2013). Luck (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that cause disease of four major food crops - wheat, rice, soybean and potato - where some diseases increased in risk while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect damage to plants to increase (Deutsch *et al.*, 2008; Paulson *et al.*, 2009). Typical scenario analyses are limited by simplistic assumptions, and work remains to evaluate how conclusions will change as more complete scenarios, such as those including migration and invasion patterns and other types of global change, are considered (Savary *et al.*, 2005; Garrett *et al.*, 2011). Effects on soil communities represent an area that needs more attention (Pritchard, 2011). Mycotoxins and pesticide residues in food are an important concern for food safety in many parts of the world, and identified as an important issue for climate change effects in Europe (Miraglia *et al.*, 2009).

7.3.2.4. Pastures and Livestock

Pastures response to climate change is complex because, in addition to the major climatic drivers (CO_2 concentration, temperature, and precipitation), other plant and management factors affect this response (e.g., plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions). Projected increases in temperature and the lengthening of the growing season should extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA. In addition, water availability may play a major role in the response of pasturelands to climate change although there are differences in species response (Izaurralde *et al.*, 2011). There is general consensus that increases in CO_2 will benefit C_3 species; however, warmer temperatures and drier conditions will tend to favour C_4 species (Izaurralde *et al.*, 2011; Hatfield *et al.*, 2011, WG2 Chapter 4).

Projected scenarios for Europe indicate that increased temperatures and CO_2 concentrations have the potential to increase herbage growth and to favour legumes more than grasses, but changes in seasonal precipitation would reduce these benefits particularly in areas with low summer rainfall (Hopkins and Del Prado, 2007). Similarly, legume content of grasslands in most of southern Australia is projected to increase to the 2070s, with larger increases in wetter locations (Moore and Ghahramani, 2013). Further implications for grasslands may arise from increased frequency of droughts, storms and other extreme events (Hopkins and Del Prado, 2007).

Impacts of climate change on feed crops and grazing systems include changes in herbage growth brought about by changes in atmospheric CO_2 concentrations and rainfall and temperature regimes, and changes in the composition of pastures and in herbage quality. The interactions among climate, plants, livestock grazing and land management practices are complex, and evaluating the impacts of climate change on these elements is difficult (Craine *et al.*, 2010). In North American cattle production systems, future increases in precipitation will probably not compensate for the declines in forage quality that accompany projected temperature increases, and cattle will experience greater nutritional stress in the future (Craine *et al.*, 2010) Also in French grasslands (Graux *et al.*, 2013) and in sown pastures in Tasmania (Perring *et al.*, 2010), results from simulations indicate that forage quality will decrease in the future.

Pastureland species in the USA may experience accelerated metabolism and advanced development with rising temperature, often resulting in changes in length of the growing season, although soil resources will often constrain temperature effects (Izaurralde *et al.*, 2011). Similar effects are projected for European grasslands, many of which may be mediated via management - sometimes with impacts on mitigation too: ruminants fed tropical legumes produced 20% less methane than those fed C_4 grasses (Archimède *et al.*, 2011).

While elevated atmospheric CO_2 concentrations reduce sensitivity to lower precipitation in grassland ecosystems and can reduce mortality and increase recovery during severe water stress events, it is still unclear how general this result is (Soussana *et al.*, 2010). Evaluating the differential responses of plant species to elevated CO_2 will require models to include mechanisms of resource capture and use among plant functional types (Lazzarotto *et al.*, 2009; Soussana *et al.*, 2010). Studies on climate change impacts on pastureland that include assessment of the mediating effects of management as well as changes in water, carbon, and nutrient cycling have been undertaken (e.g. (Rütting *et al.*, 2010; Moore and Ghahramani, 2013), but more comprehensive studies are needed (McKeon *et al.*, 2009; Izaurralde *et al.*, 2011).

Moreover, IPCC emission scenarios for many cropland regions project elevated ozone concentrations in the atmosphere to the 2050s and beyond. At the same time, crop sensitivity may decline in areas where warming is accompanied by drying, such as in central Europe (Soussana *et al.*, 2010). Parameters in models for ozone risk assessment are uncertain and model improvements will be needed to identify regions most at risk from ozone in future climates (Fuhrer, 2009). At this stage, more experiments using free-air ozone enrichment will be needed across different habitats, climates and productivity levels before generalisations about the sensitivity of pastures to ozone can be made (Fuhrer, 2009).

As livestock productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures declines (Zumbach *et al.*, 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will tend to result in animals with lower heat tolerance (Hoffmann, 2010). Recent work adds to previous understanding (AR4 Chapter 5) and indicates that heat stress in dairy cows can be responsible for the increase in mortality and economic losses (Vitali *et al.*, 2009); it affects a wide range of parameters in broilers (Feng et al, 2008); it impairs embryonic development and reproductive efficiency in pigs (Barati *et al.*, 2008); and affects ovarian follicle development and ovulation in horses (Mortensen *et al.*, 2009). The impacts of a changing UK climate on dairy cow production were analysed by (Wall *et al.*, 2010), who showed that in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century, under a medium-high greenhouse gas emissions scenario, annual production and mortality losses amounting to some £40 million by the 2080s. Given that there is a genotype-by-environment interaction on the impacts of heat stress (Bohmanova *et al.*, 2008), breeding goals that focus on production traits tend to reduce heat tolerance. Breeding goals that aim to reduce greenhouse gas emissions need to take possible future climatic conditions into account (Hoffmann, 2010). Tools to do this in

developed country situations are becoming available (e.g. (Hayes *et al.*, 2009). Developing countries may be more reliant on local breeds, most of which are not well characterized, although such breeds may be not only heat tolerant but also tolerant of poor seasonal nutrition and parasites and diseases (Hoffmann, 2010).

Host and pathogen systems will change their ranges because of climate change. Species diversity of some pathogens may decrease in lowland tropical areas as temperatures increase (Mills *et al.*, 2010). The temperate regions may become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria, which are highly sensitive to climatic conditions (Rocque *et al.*, 2008). An overall increase in suitable conditions for pathogens and vectors is expected, rather than just a shift in distribution, because minimum temperatures are increasing more than maximum temperatures (Ostfeld, 2009). Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northwards because rising temperatures increase the development rate and winter survival of vectors and pathogens (Cutler *et al.*, 2010). Diseases such as West Nile virus and schistosomiasis are projected to expand into new areas (Rosenthal, 2009). The distribution, composition and migration of wild bird populations that harbour the genetic pool of Avian Influenza viruses will all be affected by climate change, although in ways that are somewhat unpredictable (Gilbert *et al.*, 2008). The changing frequency of extreme weather events, particularly flooding, will affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are associated with increased rainfall and flooding due to El Niño-Southern Oscillation events (Gummow, 2010; Pfeffer and Dobler, 2010). In general, the impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills *et al.*, 2010; Tabachnick, 2010).

Current trends in consumption, production and environmental patterns will lead to water crises in many parts of the world (de Fraiture *et al.*, 2010). Every populated river basin in the world will experience changes in river discharge, and large human and livestock populations will experience water stress such that proactive or reactive management interventions will almost certainly be required (Palmer *et al.*, 2008). Climate change will affect the water resources available for livestock production and keeping via impacts on runoff and groundwater. In Kgatleng District, Botswana, climate change could lead to an annual increase of more than 20% in cattle water demand by 2050 because of increased temperatures under A1 SRES emission scenarios. At the same time, a decline is to be expected in the contribution of surface pan water to cattle water supply, leading to substantial increases in the abstraction of groundwater for cattle (Masike and Urich, 2008). Such problems of water supply for increasing livestock populations will be exacerbated by climate change in many places in sub-Saharan Africa and South Asia. Nevertheless, there are sufficient water resources available to satisfy global food demands during the next 50 years, but only if water is managed more effectively (de Fraiture and Wichelns, 2010). There is ample scope to improve livestock water productivity considerably (Molden *et al.*, 2010); for example, in mixed crop-livestock systems of sub-Saharan Africa via feed, water and animal management (Descheemaeker *et al.*, 2010).

7.3.2.5. Food and Fodder Quality and Human Health

Climate change is will have some adverse impacts food quality through both biotic and abiotic stresses (Ceccarelli *et al.*, 2010). These changes may affect crop quality by altering carbon and nutrient uptake and biochemical processes that produce secondary compounds or redistribute and store compounds during grain development and maturation which in turn could impact human and livestock health by altering nutritional intake. They also affect economic value by altering traits valuable to processers or the consumers. Food quality is any characteristic other than yield that is valuable to the producer or consumer, and includes properties such as protein and starch concentrations, which affect dough quality, dough strength, and loaf volume of wheat flour; chalkiness, amylose content and gelatinization temperature in rice, which affect taste; and mineral concentrations, which affect nutrient intake of consumers.

Change in N concentration, a proxy for protein concentration, is the most examined quality trait, and since AR4, studies have been extended to almost all the major food crops. Meta-analysis of 228 experimental observations finds decreases between 10 to 14 % in edible portions of wheat, rice, barley and potato, but only 1.5 % in soybeans, a nitrogen-fixing legume, when grown in elevated (540 - 958 ppm CO_2) compared to current (315 - 400 ppm CO_2) concentrations (Taub et al, 2008). The decrease in protein content of cereals grown in elevated CO_2 concentrations

was reported by many other workers (Piikki *et al.*, 2007; Hogy *et al.*, 2009; Erbs *et al.*, 2010; Ainsworth and McGrath, 2010; DaMatta *et al.*, 2010; Erda et al., 2010; Fernando *et al.*, 2012).

Mineral concentration of edible plant tissues are affected by growth in elevated CO_2 in a similar manner as N. Although there are numerous studies measuring mineral concentration, there are many minerals relevant to human health. Therefore, there are relatively few measurements for any given mineral. Although there were several studies published before the release of AR4, this topic was not covered in any depth in AR4. Meta-analysis of studies prior to 2002 finds that P, Ca, S, Mg, Fe, Zn, Mn and Cu decline by 2.5 - 20 % in wheat grain and leaves of numerous species in elevated CO_2, but K increases insignificantly in wheat grain (Loladze, 2002; Hogy *et al.*, 2009; Fernando *et al.*, 2012). Since 2002, studies generally find decreases in Zn, S, P, Mg and Fe in wheat and barley grain, but results are mixed for Ca and K, whereas limited evidence shows an increase in Cu, Mo and Pb (Hogy *et al.*, 2009; Erbs *et al.*, 2010; Fernando *et al.*, 2012). The magnitude of such decreases is likely to be affected by several factors including crop species, soil type, tissue (e.g. tuber, leaves or grain) and water status. In addition to effects of climate on plants directly, climate change-mediated soil degradation may affect nutrient composition by altering mineral availability (Lal, 2009).

The primary reason for the decline in protein concentration, and by extension mineral concentrations, is that enhanced production of carbohydrates in elevated CO_2 decreases the concentrations of all non-carbonaceous compounds because the increase in canopy carbon uptake increases without a concomitant increase in nutrient uptake. Thus, the increased amount of carbon dilutes the concentrations of other nutrients (Poorter *et al.*, 1997). The declines in nitrogen concentration are usually larger than expected from carbon dilution alone though (Taub *et al.*, 2008; Pleijel and Uddling, 2012) which indicates that nutrient uptake per unit biomass is lower under elevated CO_2 concentration. The reasons for this are unclear but altered root architecture, reduced root uptake activity and reduced flow of nutrients to the roots (Taub and Wang, 2008). Understanding the basis for these declines is imperative as it would allow for prediction of nutrient decline in various environments, and give some insight into nutrient change in relation to change in other environmental factors in the future climate.

Elevated O_3 concentrations appear to have the opposite effect as elevated CO_2. Meta-analysis of about 50 wheat experiments found that elevated O_3 increased grain protein concentration by decreasing yield (Pleijel and Uddling, 2012). For other species, studies find both increases and decreases of N and several minerals (Taub *et al.*, 2008), and as such no firm conclusions can be drawn, but they likely response similarly. Similarly, experiments examining the effect of drought on mineral concentrations find both decreases and increases in mineral concentrations (Ghorbanian *et al.*, 2011; Sun *et al.*, 2011).

Elevated CO_2 can lower the nutritional quality of flour produced from grain cereals (Hogy *et al.*, 2009; Erbs *et al.*, 2010) and of cassava (Gleadow *et al.*, 2009). When coupled with increased crop and pathogen biomass, elevated CO2 can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shriveled grains with low market value (Melloy *et al.*, 2010). High and low temperature even for a short time during reproductive growth can cause pollen sterility and shriveling of grain in wheat with consequent reduction in yield and market value. Extreme temperatures and elevated CO_2 concentrations reduce milling quality of rice by increasing chalkiness, which causes breakage during milling, leading to reduced head yield (the percentage of unbroken kernels) but increased consumer -valued traits, such as reduced amylase concentration , increased mass viscosity and increased breakdown, all of which correlate with taste, are increased (Yang *et al.*, 2007) . The cultivars, however, vary in their susceptibility (Ambardekar *et al.*, 2011; Lanning *et al.*, 2011). Rice is sensitive to daytime extreme temperature and humidity during flowering and also to high night-time temperature causing a decrease in rice eating quality and assimilates accumulation, and yield (Okada *et al.*, 2009; Wassmann *et al.*, 2009).

There is robust evidence and high agreement that elevated CO_2 on its own likely results in decreased N concentrations. Combining knowledge of N and mineral studies, there is *medium evidence* and *medium agreement* that mineral concentrations will decline. The majority of these data are from wheat, with comparatively little information from key crops such as maize, rice, potato and cassava; thus magnitudes are uncertain for the species. Increases in CO_2 concentration are global and uniform, thus this effect will have global impacts, but confidence in this effect does not imply confidence in changes regarding human health for several reasons. First, elevated CO_2 can increase yield of minerals (g mineral per m^2 land area) even though concentrations are decreased (Duval *et al.*,

2011). Therefore, for any group for which increased crop yields allows for greater consumption (e.g., because they produce and consume the food directly, or through effects of prices) intake of calories and minerals could increases, despite lower mineral concentrations. Furthermore, since calorie intake is the primary concern in many food insecure populations, even if intake of minerals is decreased, those negative effects could be outweighed by increased calorie intake. Second, altered temperature, precipitation and ozone concentrations affect nutrient concentrations and their effects are globally variable. Third, changes in mineral concentrations do not directly relate to changes in consumption since many foods are processed in ways that affect nutrient concentrations, e.g., the nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Lastly, impacts on health must take into account current diets. Decreased mineral intake will matter for those who currently do not meet, or just barley meet, requirements, but will not affect those who already exceed requirements. Little is known about combined effects of climate change factors on food quality or the economic and behavioral changes that will occur. Thus, there is little to no confidence regarding effects of climate change on human health through changes in nutrient composition. Hence, a complete understanding of how climate-induced changes in food quality will impact human health in different environments and how this information will be used to make predictions about impacts on health is needed.

7.3.2.6. Fisheries and Aquaculture

The fisheries and aquaculture sector differs from mainstream agriculture and is characterized by distinct interactions and needs in relation to climate change. Capture fisheries in particular, comprising the largest remaining example of harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic and nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries and rapid development of aquaculture. This demand will increase over the next 20 to 30 years at least: (Merino *et al.*, 2012) forecast that in addition to a predicted small increase in marine fisheries production, between 71 and 117 MT of fish will need to be produced by aquaculture to maintain current average *per capita* consumption of fish. Climate change is an additional threat to the sustainability of capture fisheries and aquaculture development, adding to the threats of over-fishing and other environmental impacts (FAO, 2009). Expected changes in the intensity, frequency and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification and changes in precipitation with associated changes in groundwater and river flows are expected to result in significant changes across a wide range of aquatic ecosystem types and regions. There is no conclusive evidence at this stage, but the potential risks of climate change enabling the spread of pathogenic species has been raised and there are some concerns that, for example, poleward increases in temperature could lead to the spread of pathogens with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

7.3.2.6.1. Mean and extremes of temperature and precipitation

There is widespread agreement that, under most emission scenarios, increasing mean temperatures will lead to changes in the distribution of marine fish and invertebrate species. In general, the distribution of species will shift towards the poles as has already been observed in, for example, the North Sea (Brander, 2007)) and Australia (Hobday, 2010) JP: I have highlighted the following in red for you to decide if it needs to be deleted,Chapter 6 of this volume). These shifts will result in positive and negative impacts on fisheries production with the direction of change varying from locality to locality and species to species. Overall, increased temperatures are expected to reduce ecosystem productivity in most tropical and subtropical oceans, seas and lakes and to increase productivity in high latitudes. Projections based on a dynamic bioclimate envelope model under the SRES A1B scenario suggested that climate change could lead to an average 30–70% increase in fisheries yield from high-latitude regions (>50^{o} N in the northern hemisphere), but a decrease of up to 40% in the tropics by 2055 compared to yields obtained in 2005 (Cheung *et al.*, 2010). A recent study using a suite of models linking physical, ecological, fisheries, and bioeconomic processes projected that, under the A1B scenario, the global yield from ‘large’ fish could increase by 6% and that of the ‘small fish’ used in fishmeal production by 3.5%. This forecast was predicated on the assumption that marine fisheries and fish resources would be managed sustainably (Merino *et al.*, 2012). A study on the effects of climate warming on marine fish along the Portuguese coast forecast, under the A2 and B2 emission scenarios, that fish species richness would increase, potentially creating opportunities for the development of new commercial

fisheries (Vinagre *et al.*, 2011). Fulton (2011) used available end-to-end models to forecast the impacts of climate change under the A2 scenario across approximately two-thirds of Australia's EEZ. The results indicated that by 2060 the large-scale commercial fisheries in all of the regions that were covered by the models would experience an overall increase of 90% in their economic returns, although differing across sectors. The change in returns for the small-scale sector varied between the regions from a decrease of 30-51% in some regions to an increase of 9-14% in another. The difference between the sectors was because the large-scale fisheries had greater flexibility to adapt to changes in distribution, composition and abundance of their target species (Fulton, 2011). These and other available forecasts demonstrate substantial differences in the direction and magnitude of impacts of climate change on fisheries production around the world, driven by different physical and biological attributes and the ability of fisheries operations and management to adapt to the changes that do occur.

The changes in marine yields projected by (Cheung *et al.*, 2010) result from changes in distribution of important fish stocks. In the case of freshwater fisheries, natural boundaries will frequently restrict the ability of species to change distribution. Endemic species, those in fragmented habitats and those in aquatic systems with a predominantly east–west orientation will be particularly restricted (Ficke *et al.*, 2007), as will food production systems dependent on them.

Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to cope with them. For example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than 14ºC diurnally (Pratchett *et al.*, 2011). Nevertheless, changes in temperature extremes are expected to have impacts in some cases. For example, a study on salmon populations in Washington State, USA by (Mantua *et al.*, 2010) demonstrated the important impacts of seasonal variations and extremes, as opposed to means, on population responses to climate change. The study concluded that warming in winter and spring would have some positive impacts while increased summertime stream temperatures, seasonal low flows and changes in the peak and base flows would have negative impacts. Coral reefs are particularly susceptible to extremes in temperature: temperatures 1 or 2ºC in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between endosymbiotic dino-flagellates and their coral hosts leading to coral bleaching. Large scale bleaching of coral reefs has increased in recent decades both in intensity and frequency (Hoegh-Guldberg *et al.*, 2007); Box 5-3).

Reliable fine scale projections are not available at present because of the ecological complexity of the responses as well as the potential role of human adaptation in minimising risks and taking advantage of new opportunities.

7.3.2.6.2. Impact of ocean acidification

The impact of increasing CO2 concentrations on coral reefs as a result of higher concentrations of carbonic acid in the ocean reducing the availability of carbonate to the reef building organisms is addressed in the Cross-chapter ocean acidification box (IPCC 2014, WG2). It is reported there, citing the original references, that the annual economic cost of ocean-acidification-induced coral reef loss by 2100 has been estimated to be 870 and 500 billion USD respectively for A1 and B2 SRES emission scenarios and that the global cost of loss of production of molluscs could be over 100 billion USD by 2100.

7.3.2.6.3. Combined impacts on fish and seafood production

Climate change is modifying the distribution of marine and freshwater species with a general displacement towards the poles and is leading to changes in the size and productivity of suitable aquatic habitats. This will have a mixture of negative and potentially positive impacts which will vary from locality to locality. The ability to take advantage of new opportunities brought about by these changes will depend on the adaptive capacity of countries and local communities.

Where these ecological changes are significant, countries and communities will need to adapt through, for example, changes in fishing and aquaculture practices and operations. Given the proximity of fishing and aquaculture sites to oceans, seas and riparian environments, extreme events can be expected to have impacts on the associated

infrastructure and to affect safety at sea and for communities, with those living in low-lying areas at particular risk. In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries production will be at risk. The impacts of climate change on the fisheries and aquaculture sector will have implications for the four dimensions of food security i.e. availability of aquatic foods, stability of supply, access to aquatic foods, and utilization of aquatic products (FAO, 2009).

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

As indicated in the discussion in 7.1.1 and Figure 7-1, food security is dependent on access and consumption patterns, food utilization and nutrition, and overall stability of the system as much as food production and availability. The overall impact of climate change on food security is considerably more complex and potentially greater than projected impacts on agricultural productivity alone. Figure 7-1 indicates the main components of food security and their key elements. All of these will be affected by climate change to some extent. For example, climate change effects on water, sanitation and energy availability have major implications for food access and utilization as well as availability. Likewise, changes in the frequency and severity of climate extremes can affect stability of food availability and prices, with consequent impacts on access to food.

7.3.3.2. Accessibility, Utilization, and Stability

7.3.2.2.1. Climate change impacts on access

As noted in the discussion in section 7.1.3, change in the levels and volatility of food prices is a key determinant of food access. Given the hypothesis that climate change will be a contributing factor to food price increases, and hence its affordability, the vulnerability of households to reduced food access depends on their channel of food access (*medium evidence; medium agreement).* Table 7-1 divides households into five main categories of food access, indicating their relative impacts of food price increases.

[INSERT TABLE 7-1 HERE
Table 7-1: Households divided into five categories of food access, indicating the impacts for them of food price increases.]

Concern about the impact of increased food prices on poverty and food security arises due to the high share of income that poor consumers spend on food, thus generating a disproportionately negative effect of price increases on this group (FAO, 2011). A recent study by the World Bank estimated a net increase of 44 million people in extreme poverty in low and middle income countries as a result of food price increases since June 2010 (Ivanic *et al.*, 2011).

Recent studies have indicated that the distribution of net food buyers and net food sellers varies considerably across countries and can be expected to change with the process of economic development (Zezza *et al.*, 2008; Aksoy *et al.*, 2010; FAO, 2011) . Changing consumption patterns associated with dietary transitions that accompany income growth, urbanization, market development, and trade liberalization determines the rate and nature of food demand growth and nutritional levels, and thus is a key determinant of global and local food security (Kearney, 2010). However the evidence base on potential climate change impacts on consumption patterns, or on other non-production elements of food security is thin (*limited evidence, low agreement*), particularly when compared with the literature on climate change impacts on food production and availability.

The variation in the distribution and vulnerability to loss of food access across household types indicates the complexity of assessing the potential effects of climate change on food access at future time periods where these factors may be expected to change. Nonetheless, there are reasons for concern about climate change impacts on food access due to the high rates of food insecurity and significant share of population in many low income countries of one of the most vulnerable groups to loss of access: e.g. agricultural producers who are net food buyers. Similarly,

low income agricultural dependent economies that are net food importers, which are those that already have high rates of food insecurity, could experience significant losses in food access through a double negative effect on reduced domestic agricultural production and increased food prices on global markets.

7.3.2.2.2. Climate change impacts on stability

There is increasing evidence and confidence in the effect of climate change on increasing the incidence and frequency of some types of climate extreme events (IPCC, 2012), and this will have significant impacts on food security (*medium evidence; medium agreement*) Recent experience with global climate pattern impacts on food security indicate the potential nature and magnitude of increased climate extremes. An impact assessment of the 2010 Pakistan floods surveyed 1800 households 6 months after the floods and found that 88% of the households reported income losses of up to 50%, with significantly higher rates in rural than urban areas (Kirsch *et al*., 2012). The same study indicated that loss of key services such as electricity, sanitation and clean water resulted in lower standards of living even in the wake of significant relief attempts, again with significantly heavier effects on rural populations (Kirsch et al., 2012). The Russian heat wave of 2010 and subsequent export ban contributed to the more than doubling of global wheat prices by the end of the year. The degree to which these price increases affected domestic consumers and poverty depended on national responses in importing countries, although a significant net negative effect on poverty was found (Ivanic *et al*., 2011).

Increased incidence of climate extremes increases uncertainty, which mitigates incentives to invest in agricultural production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor smallholders with limited or no access to credit and insurance. Greater exposure to climate risk, in the absence of well-functioning insurance markets, leads to: 1) greater emphasis on low-return but low-risk subsistence crops (Roe and Graham-Tomasi, 1986; Fafchamps, 1992; Heltberg and Tarp, 2002), 2) a lower likelihood of applying purchased inputs such as fertilizer (Kassie et al., 2008; Dercon and Christiansen, 2011), 3) a lower likelihood of adopting new technologies (Feder *et al*., 1985; Antle and Crissman., 1990), and 4) lower investments (Skees *et al*., 1999). All of these responses generally lead to both lower current and future farm profits *(robust evidence, high agreement*) (Rosenzweig and Binswanger, 1993; Hurley, 2010).

It is also well documented that in many rural areas, smallholders in particular do not have the capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the same location (Dercon, 2004; Skoufias and Quisumbing, 2005; Dercon et al., 2006; Fafchamps, 2009; Prakash, 2011). Any increases in climate extremes will exacerbate the vulnerability of all food insecure people, including smallholders (*robust evidence, high agreement*). Currently, smallholders rely to a large extent on increasing labor off-farm where possible (Fafchamps, 1999; McPeak, 2004; Kazianga and Udry, 2006), but also by decreasing both food consumption and non-food expenditures, such as those on education and healthcare (Frankenberg, 1999; Skoufias and Quisumbing, 2005) (*medium evidence, high agreement*). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover current deficits (*limited evidence, medium agreement*) (Kazianga and Udry, 2006; Carter and Lybbert, 2012). Reductions in food consumption, sales of productive assets, education and healthcare can lead to long-term losses in terms of income-generation and thus to future food security (*limited evidence, medium agreement*) (Hoddinot and Maluccio, 2002; Skoufias and Quisumbing, 2005). Increased uncertainty of future climate conditions and increases in climate extremes will increase food insecurity unless these significant barriers to consumption and asset smoothing can be addressed (*medium evidence, medium agreement*).

7.3.2.2.3. Climate change impacts on utilization

Climate change impacts on utilization may come about through changes in consumption patterns in response to shocks, as well as changes in nutrient content of food as well as food safety (*medium evidence; medium agreement*). Rationing consumption to prioritize calorie-rich, but nutrient poor foods is another common response (Bloem *et al*., 2010). The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing vulnerabilities – and lead to long term loss of health, productivity capacity and low incomes (*medium evidence;*

medium agreement) (Bloem *et al*., 2010; Alderman, 2010; Brinkman *et al*., 2010; Campbell *et al*., 2010; Sari *et al*., 2010). The biological effects of climate change on nutrient content of foods is one of main pathways for effects on utilization. A summary of recent literature on the impacts of climate change on the composition of nutrients in food items is given in HLPE (2012). Research on grains generally shows lowering of protein content with elevated temperature and CO_2 levels (Ainsworth and McGrath, 2010; Erda et al., 2005; Hatfield *et al*., 2011). There is good agreement that for plant-derived foods, mycotoxins are considered the key issue for food safety under climate change (Miraglia *et al*., 2009). The impacts of climate change on mycotoxins in the longer term are complex and region-specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts of the tropics, but in colder tropical regions and temperate zones, infections may increase (Cotty and Jaime-Garcia, 2007).

7.3.4. Land Use Change and Autonomous Adaptation

As noted in the AR4, changes in land use, for example adjusting the location of crop production, are a potential adaptation response to climate change. Studies since the AR4 have confirmed that high latitude locations are likely to become more suitable as the total time regions (Iqbal *et al*., 2009). Trnka et al. (2011), for example, examined projections of eleven agro-climatic indices across Europe, and found that declines in frost occurrence will lead to longer growing seasons, although temperature and moisture stress will likely lead to greater inter-annual variability in crop suitability. The potential influence of pests and diseases is commonly beyond the scope of such studies (Gregory et al., 2009).

For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing season, there is a likelihood that the length of the growing season and overall suitability for crops will decline (*medium evidence, medium agreement*) (Jones and Thornton, 2009; Zhang and Cai, 2011). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat stressed by the 2050s, whilst temperate wheat environments are likely to expand northwards as climate changes (Ortiz *et al*., 2008). Similarly, by 2050, the majority of African countries will experience climates over at least half of their current crop area that lie outside the range currently experienced within the country (Burke *et al*., 2009). The majority of these novel climates have analogues in other African countries. In mountainous regions, where temperature varies significantly across topography, changes in crop suitability can be inferred from the variation of temperature across topography. The resulting vertical zones of increasing, decreasing and unchanging suitability can be relatively robust in the face of uncertainty in future climate (Schroth *et al*., 2009).

The interaction between water resources and agriculture is likely to be increasingly important as climate changes. For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions scenario, irrigation has significant adaptation potential (Piao *et al*., 2010). However, limitations to availability of water will affect this potential (Frieler *et al*., 2013). Changes in water use, including increased water diversion and development to meet increasing water demand, and increased dam building will also have implications for inland fisheries and aquaculture, and therefore for the people dependent on them (Ficke *et al*., 2007; FAO, 2009). In the case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in some way on fisheries and aquaculture which will be seriously impacted by human population growth, flood mitigation, increased offtake of water, changes in land use and overfishing, as well as by climate change (Brander, 2007). Ficke et al. (2007) reported that at that time there were 46 large dams planned or already under construction in the Yangtze River basin, the completion of which would have detrimental effects on those dependent on fish for subsistence and recreation.

The models used in projections of land suitability and cropland expansion discussed above rely on assumptions about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area with model predictions. The location of the margin between cropping land and extensive grazing in southern Australia has varied with decadal climate conditions and is projected to shift towards the coast with hotter and drier conditions, notwithstanding the positive impacts of elevated CO_2 (Nidumolu et al., 2011). Recent trends in climate have seen reductions in cropping activity consistent with these projections (Nidumolu et al., 2011).

The application of first-generation biofuel conversion technologies have expanded the uses for traditional commodities such as maize, oil seeds, and sugarcane, enabling farmers to market their crops beyond the traditional food, feed or industrial food-processing uses. Such changes in land use have potentially adverse consequences for food security. There are a number of developing countries that are relatively food secure, and have a higher demand for fossil-based fuels – Brazil, Malaysia, Peru, Argentina, and Thailand–. A number of these countries which are export-oriented and have relatively large areas of land available are currently expanding biofuel production in order to meet both domestic and international demand (Ewing and Msangi, 2009). However, the expansion of biofuel production has created new linkages, trade-offs, and competition between the agricultural and energy sectors. It has also introduced new food-security risks and new challenges for the poor, particularly when natural-resource constraints have led to trade-offs between food and biofuel production and also to rising food prices (FAO, 2008; von Braun and Torero, 2009; Chum et al., 2011). The current food crop based biofuels are of concern as their development will also exacerbate food insecurity particularly in many of developing countries. Biofuels targets imply that an additional 140 and 150 million people may be at risk of hunger by 2020. Africa and South Asia will account for over two-thirds of those people most affected (Fischer *et al*., 2009).

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

Crop productivity remains the most well studied aspect of food security impacts from climate change, with many projections published since AR4. These newer studies confirm many of the patterns identified in AR4, namely that tropical areas fare worse than temperate areas for small amounts of warming, and all areas are projected to have negative yield impacts past 3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall (Challinor *et al*., 2013). One exception is that more recent studies often show negative impacts for temperate wheat for 1-3 °C local warming, whereas AR4 showed primarily positive responses at these temperatures.

Figure 7-6 shows the changes in mean crop yield in twenty-year bins, from a meta-analysis of over 1800 projections (Challinor *et al*., 2013), including cases with no adaptation and a range of incremental adaptations. Taking the data as an indication of risk of crop yield reduction shows that reductions in mean yield become *more likely than not* from the 2030s. Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. Some important regional differences are masked in the figure. From the 2070s onwards, all of the positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are *very likely* by this time. This is consistent with the analysis of Knox *et al*. (2012). A recent model intercomparison of global gridded crop models (Rosenzweig *et al*., 2013) presents a similar pattern for projections from site-based crop models.

[INSERT FIGURE 7-6 HERE
Figure 7-6: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Taken from (Challinor *et al*., 2013).]

Fewer studies have explicitly compared projections for different regions or crops to identify areas at most risk. (Lobell *et al*., 2008) used a statistical crop model with 20 GCMs and identified South Asia and Southern Africa as two regions that, in the absence of adaptation, would likely suffer negative impacts on several important crops. Yields changes have also been assessed by regional meta-analyses: Knox *et al*. (2012) found yield reductions of up to 50% in the second half of the century for Sub-Saharan Africa and South Asia, with wheat, maize, sorghum, and millets more affected than rice, cassava, and sugarcane.

Changes in the interannual variability of yields are likely to be important in determining future stability of food availability and access. Figure 7-7 shows projected changes in the coefficient of variation of yield from some of the few studies that publish this information. The data shown are consistent with reports of CV elsewhere: Müller *et al*. (2013) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% grid cells, and a decrease of more than 5% in 29% of cases. Increases in CV can be due to reductions in mean yields

and/or increases in standard deviation of yields, and often simulated changes are a combination of the two. However, many studies reported increases in standard deviation, for example (Challinor *et al*., 2010) projected increasing occurrence of extremely low crop yields due to heat and water stress. Teixeira *et al*. (2013) report that under SRES A1B for 2070-2100 high temperature stress is likely to affect many parts of the globe, including temperate regions. Semenov and Shewry (2011) also find evidence from models that temperate heat stress will be an important determinant of yield from the 2050s. Thus temperature extremes due to changes in the distribution of climate are likely to increase yield variability. Overall, there is *medium confidence* that climate change will increase variability in crop yield in many regions (*medium evidence, medium agreement*).

[INSERT FIGURE 7-7 HERE
Figure 7-7: Projected percentage change in coefficient of variation (CV) for wheat (gold), maize (green), rice (blue) and C4 crops (red) taken from C2010 (Challinor *et al*., 2010), B2012 (Berg et al., 2012), T2009 (Tao et al., 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban et al., 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies are for China.]

Given an increasing likelihood that mean global warming will be in excess of 2ºC (New et al. 2011) and perhaps up to 4ºC by 2100, studies have examined the effects of such warming on two very different regions; sub-Saharan Africa and northern Europe (Finland). With *medium evidence* and *high agreement*, the studies (Rötter et al., 2011; Thornton et al, 2011) conclude that positive effects of modest warming and increased CO_2 levels on crop yields are likely to be reversed at minimum temperatures increases of 4ºC, leading to grain yield decreases in excess of 20% in relation to current conditions (Rötter et al. 2011). An analysis for sub-Saharan Africa predicted overall decreases of 19% for maize yields, 68% decrease for bean yields and a small increase for fodder grass (*Brachiaria descumbens*) given 5ºC global average warming (Thornton *et al*., 2011).

Weed populations and demographics are expected to change, with an overall poleward migration in response to warming (Ziska *et al*., 2011). An overview of crop and weed competitive studies indicate that weeds could limit crop yields to a greater extent with rising levels of carbon dioxide per se (Ziska, 2010). This may be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity inherent in large cropping systems (Treharne, 1989); such plasticity, in turn, would be advantageous in a rapidly changing climate. Finally, chemical control of weeds, which is the preferred management method for large-scale farms, may become less effective (*medium evidence, medium agreement*), with increasing economic and environmental costs.

Climate change effects on productivity of food systems will alter land use patterns, both in terms of total area sown to crops and the geographic distribution of that area. Given expected trends in population, incomes, bioenergy demand, and agricultural technology, global arable area is likely to increase from 2007 to 2050 (medium evidence, high agreement), with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer *et al*., 2009), +10-20% (Smith *et al*., 2010), and +5-25% (Schmitz *et al*., 2013) (medium evidence, medium agreement). Not all such studies included the effects of global warming. Where this is the case, estimates range from a 20% increase in cropping area (Schmitz *et al*., 2013) to a decline of 9% (Zhang and Cai, 2011), but with large regional differences (limited evidence, low agreement). Countries at northern latitudes and under the current constraint of low temperature may increase cultivated area (limited evidence, low agreement). The generally lower nutrient quality of soils and the lack of available and necessary infrastructure required to convert virgin land into productive arable land, make estimates of any actual increase in harvested cropping areas highly uncertain, with this uncertainty increasing even more after 2050.

7.4.2. Projected Impacts on Fisheries and Aquaculture

7.4.2.1. Capture Fisheries

There have been a number of studies on the probable impacts of climate change on capture fisheries (see also Chapters 6 and 30). These take the form of studies on single-species (e.g. tuna species: (Loukos *et al.*, 2003; Lehodey *et al.*, 2010); and cod: (Drinkwater, 2005), ecologically significant taxonomic groups (e.g. coral reefs: (Hoegh-Guldberg *et al.*, 2007; Munday *et al.*, 2008), geographical regions (e.g. Australia: (Brown *et al.*, 2010) North Sea: (Cook and Heath, 2005; Hiddink and Hofstede, 2008); and the Pacific island countries and territories: (Bell *et al.*, 2011) and global (e.g. (Brander, 2007; Cheung *et al.*, 2010). All of them make considerable effort to minimise uncertainties but inevitably rely on underlying assumptions and retain considerable residual uncertainty.

Simulation studies on skipjack and bigeye tuna in the Pacific under the B1 and A2 scenarios suggest that the vulnerability of skipjack tuna to climate impacts in 2035 is low under both scenarios but moderate under B1 and high under A2 by 2100. Projections under the A2 scenario suggest a 32% decrease in biomass of skipjack in the western and 50% increase in the eastern Pacific Ocean by 2100 compared to biomasses in 2000, but the authors express lower confidence (evaluated by them at 5-33% confidence) in these results than for the B1 scenario where confidence is evaluated at 33-66% confidence (Lehodey, 2011). For bigeye tuna, the results are broadly similar. These shifts in distribution would tend to favour some of the smaller Pacific Island Countries and Territories (PICTs) in the central Pacific which are particularly dependent on revenues from sale of tuna fishing rights (Bell *et al.*, 2011). Tropical tuna fisheries are also discussed in Chapter 30.6.1.1.1.

Coastal fisheries make significant contributions to food security and livelihoods of rural and urban populations in the PICTs where, for the majority of them, average fish consumption is more than 50 $kg.person^{-1}.year^{-1}$. The food requirements of the human population of this area are predicted to increase by between 20 and 60% over the next 20 years (Bell *et al.*, 2011). Climate change is expected to impact directly on the productivity of coastal fisheries in the PICTs through increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral reefs, mangroves, sea-grasses and intertidal flats (Pratchett *et al.*, 2011). Extreme events such as increased severity of tropical cyclones could also impact on some species. Under both B1 and A2 emissions scenarios, the vulnerability in 2035 (as estimated through the framework described in Bell et al. (2011b) of coastal fisheries as a whole is considered to be low. Under the B1 emissions scenario, the overall vulnerability of coastal fisheries is considered to be moderate in the PICTs in the west of the region and low for those in the East. The high emissions A2 scenario is expected to lead to major changes in the tropical Pacific, for example through deterioration of coral reef habitats and weakening of the South Equatorial Current and Counter Current. The net result is forecast to be a reduction in coastal fisheries production by 2100, under the A2 scenario, of by 20-35% in the west and 10-30% in the east, leading to an estimated vulnerability of moderate to high in the west and moderate in the east (Pratchett *et al.*, 2011).

In a broad-based modelling study (Brown *et al.*, 2010) forecast that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000-2050 as a result of small increases in nutrient availability from changes in ocean stratification and temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general, to benefit fisheries catch and value. As another example, described in Section 2.1, impacts on fish and fisheries in the North Sea are widely expected to vary from area to area and species to species.

7.4.2.2. Aquaculture

Complementing the study by Mantua et al. (2010) on the impacts of climate change on salmon populations in Washington State, USA, (Huppert *et al.*, 2009) considered the impacts on the coast of that state. They concluded that there would be a number of physical and chemical consequences including inundation of low-lying coastal areas from sea level rise, coastal flooding from major storm events and increased ocean temperatures and acidification. These physical and chemical drivers are forecast to create a number of problems for the important shellfish aquaculture industry in the state arising from reduced growth and reproductive rates as a result of increased

temperatures, inundation of existing shellfish habitats from sea level rise, increased incidence of harmful algal blooms and higher rates of mortality as a result of greater acidity of sea water and resulting decreased calcification rates in skelton and shell formation. The authors report that the socio-economic impacts cannot be quantified at this stage but are considered to be substantial.

Aquaculture is considered to be under-developed in the island states and territories of the tropical Pacific. At present just over 20 000 people are estimated to be employed in aquaculture enterprises throughout the region, including the culture of black pearls in French Caledonia. Starting from this low base, pond aquaculture is seen as an important contributor to meeting the shortage of fish required for food security in the region. Using a structured vulnerability framework which uses the B1 and A2 emission scenarios to make forecasts to 2035 and 2100 (Bell *et al*., 2011b), it was concluded that production of freshwater species such as tilapia, carp and milkfish will probably benefit from the expected climate changes, while coastal enterprises are expected to encounter problems in the same time horizons, varying according to species. The drivers of these trends include changes to temperature, rainfall and sea-level rise (Pickering *et al*., 2011).

7.4.2.3. National and Regional Vulnerability

The consequences of the many and diverse impacts on capture fisheries and aquaculture, both positive and negative, on food security are more difficult to estimate than the biological and ecological consequences. A preliminary but informative study by (Allison *et al*., 2009) attempted to estimate the vulnerability of the economies of 132 countries to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios (also discussed in Chapter 6.4.1.1.2). They estimated vulnerability as a composite of three components: exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries (measured by total fisheries production, contribution of fisheries to national employment, export income and dietary protein) and adaptive capacity within the country (a composite index derived from life expectancy, indicators of education levels, various indicators of governance effectiveness and size of economy). This analysis suggested that under both scenarios several of the least developed countries were also amongst the most vulnerable. They included countries in central and western Africa, Peru and Columbia in South America and four tropical Asian countries. Food security will be a major consideration in these vulnerable countries.

7.4.3. Projected Impacts on Food Prices and Food Security

AR4 presented a summary of food price projections based on five studies that used projected yield impacts as inputs to general or partial equilibrium models of commodity trade. Many additional projections of this type have been made since AR4, expanding the number of trade models used, the diversity of yield projections considered, and the disaggregation of prices by commodity (Hertel *et al*., 2010; Baldos and Hertel, 2013; Lobell *et al*., 2013; Nelson *et al*., 2013). Many of the studies did not include CO_2 effects, which is sometimes justified on the grounds that studies are concerned with "worst-case" scenarios, or that the bias from omitting positive CO_2 effects balances the known bias from omitting negative effects of elevated O_3 and increased weed and pest damage.

Based on these studies, it is *very likely* that changes in temperature and precipitation, without considering effects of CO_2, will lead to increased food prices by 2050, with estimated increases ranging from 3-84%. The combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices, with a range of projected impacts from -30% to +45% by 2050. One lesson from recent model intercomparison experiments (Nelson *et al*., 2013) is that the choice of economic model matters at least as much as the climate or crop model for determining price response to climate change, indicating the critical role of economic uncertainties for projecting the magnitude of price impacts.

The AR4 concluded that climate change was likely to result in higher real prices for food past 2050. This conclusion remains intact with *medium confidence*, albeit with a relative lack of new studies exploring price changes to 2100 or beyond. The pathways by which price changes can affect food security are outlined in section 7.3. A limited number of studies have estimated the effects of price changes on food security and related health outcomes. Nelson *et al*.

(2009) project that, without accelerated investment in planned adaptations, climate change by 2050 would increase the number of undernourished children under the age of 5 by 20-25 million (or 17-22%), with the range including projections with and without CO_2 fertilization. Lloyd et al. (2011) used the projected changes in undernourishment from Nelson (2009) to project the impact of climate change on human nutrition, estimating a relative increase in moderate stunting of 1–29% in 2050 compared with a future without climate change. Severe stunting was projected to increase by 23% (central SSA) to 62% (South Asia). Baldos and Hertel (2013) estimate that climate change results in an increase in global malnourished population by 49 million (11%) in 2050, but that the combined effects of climate change and CO_2, which results in yield increases in their study, reduces the number by 66 million (15%).

In summary, there is *medium confidence* (*limited evidence, high agreement*) that if global yields are negatively impacted by climate change, there would be a resulting increase in both food prices and the global headcount of food insecure people. However, it is only *about as likely as not* that such global yield effects will be experienced by 2050 as the net effect of climate and CO_2 changes, but *likely* that such changes will occur later in the 21st century. At the same time, it is *likely* that overall growth and development will remain a relatively stronger driver of food security over the next few decades, particularly when accompanied by changes in institutions and policies (Goklany, 2007; Parry *et al*., 2009). Importantly, all of the studies that project price impacts assume some level of on-farm agronomic adaptation, often by optimizing agronomic practices within the model. Most, but not all, also prescribe income growth rates as exogenous factors, despite the fact that incomes are heavily dependent on agriculture in many poor countries. One study that accounted for income effects found that, in countries such as Indonesia that had both a large share of poverty in agriculturally dependent households and yield impacts that were small relative to other regions, poverty was reduced by the effects of climate change (Hertel *et al*., 2010). However, in most countries the positive income effects of higher prices could not outweigh the costs of reduced productivity and higher food prices.

Recent work has also highlighted that productivity in many sectors besides agriculture are significantly influenced by warming, with generally negative effects of warming on economic output in tropical countries (Hsiang, 2010; Dell *et al*., 2012). Given the importance of incomes to food access, incorporating these effects into future estimates of food security impacts will be important. Conflict is also known to be an important factor in food security (FAO, 2010a), and evidence of climate variability effects on conflict risk (Hsiang *et al*., 2011) indicates a need to also consider this dimension in future work.

The impacts of climate change on food production and food security will depend on interactions between the multiple drivers outlined above. The timing of extreme events, which are expected to become more frequent (IPCC, 2012), is one such driver. Extremes contribute to variability in productivity (Figure 7-7) and can form part of compound events that are driven by common external forcing (e.g. El Niño), climate system feedbacks, or causally unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different regions, may have negative impacts on food security, particularly against the backdrop of high food price volatility (Figure 7-4). There are very few projections of compound extreme events (IPCC, 2012), and interactions between multiple drivers are difficult to predict. Thus nonlinear interactions in food systems may mean that thresholds are reached through non-predicted mechanisms. Effective monitoring and prediction, and building resilience into food systems, are likely to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn *et al*., 2010).

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7.5. Adaptation and Managing Risks in Agriculture and Other Food System Activities

7.5.1. Adaptation Needs and Gaps based on Assessed Impacts and Vulnerabilities

7.5.1.1. Methods of Treating Impacts in Adaptation Studies – Incremental to Transformational

The pervasiveness of climate impacts on food security and production (Section 7.2), the commitment to future climate change from past greenhouse gas emissions (cross reference to WGI) and the very high likelihood of additional climate changes from future greenhouse gas emissions (cross reference to WGI) means that some level of adaptation of food systems to climate change will be necessary. Here we take adaptation to mean reductions in risk and vulnerability through the actions of adjusting practices, processes and capital in response to the actuality or threat of climate change. This often involves changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized. Adaptation can also enhance opportunities from climate change (IPCC AR4 Chapters 5 and 17). These adaptations will need to be taken in the context of a range of other pressures on food security such as increasing demand as a result of population growth and increasing per capita consumption (Section 7.1).

In the period since the AR4 the literature on adaptation and food production has increased substantially, although there has been less focus on adaptations to food systems and on value chains: the linked sets of activities that progressively add value as inputs are converted into products the market demands. Many adaptation frameworks or approaches have been published, informing the approach in the AR4 which addressed both autonomous and planned adaptations. Autonomous adaptations are incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced (Glossary). They include coping responses and are reactive in nature. Planned adaptations are proactive and can either adjust the broader system or transform it (Howden *et al.*, 2010). Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that whilst many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favourable for effective adaptation including investment in new technologies and infrastructure. Building adaptive capacity by decision-makers at all scales (e.g. Nelson et al. 2008) is an increasingly important part of the adaptation discourse which has also further addressed costs, benefits, barriers and limits of adaptation (e.g. Adger et al. 2009).

The sector-specific nature of many adaptations means that sectors will initially be addressed separately below.

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (Chapter 5 AR4). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times and crop cultivars and species (e.g. Olesen et al. (2011) and marketing arrangements (WG II Box 9-4, Fujisawa and Koyabashi 2011) although this response is not ubiquitous (Bryan et al. 2009). There are a large number of potential adaptations for cropping systems and for the food systems of which they are part, many of them enhancements of existing climate risk management and all of which need to be embedded in the wider farm systems and community contexts.

The possibility of extended growing seasons because of higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds (Krishnan et al, 2007; Magrin et al., 2009; Travasso et al., 2009; Laux et al., 2010; Stockle et al., 2010; Shimono et al., 2010, Deressa et al. 2009. Van de Giesen et al. 2008, Mary and Majule 2009, Meza and Silva 2009, Olesen et al. 2011, Tao and Zhang 2010, Tingem and Rivington 2010, Cho et al. 2012). Aggregated across studies, changing planting dates may increase yields by a mean of 13% but with substantial variation (Figure 7-8). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura 2010), seedling transplanting and seed priming and these adaptations can be integrated with varieties with greater thermal time

requirements so as to maximize production benefits and to avoid late season frosts (e.g. Tingem and Rivington 2010, Crimp et al. 2012, Cho et al. 2012). In some situations early sowing may allow double cropping where currently only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008) and the double crop wheat/soybean in the southern pampas of Argentina (Monzon et al, 2007), increasing productivity per unit land although increasing nitrogen and water demand at the same time. However, in Mediterranean climates, early sowing of cereals is dependent on adequate planting rains in autumn and climate projections indicate that this may decrease in many regions (WG 1 cross-reference), limiting the effectiveness of this adaptation (Figure 7-8) and possibly resulting in later sowings than are currently practiced. In such circumstances, use of short duration cultivars could be desirable so as to reduce exposure to end of season droughts and high temperature events (Orlandini et al. 2008; Walter et al. 2010). There is *medium confidence* (*high agreement, medium evidence*) that optimisation of crop varieties appears to be an effective adaptation, increasing yields by around 50% compared with the use of current varieties and planting schedules when aggregated across studies (Figure 7-8). Flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Meza and Silva 2009, Deressa et al. 2009). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop risk (e.g. Cooper et al. 2008; Challinor *et al*., 2009; Baethgen 2010, Li et al. 2010) although care is needed to ensure that the provision of forecasts does not increase existing inequities in farming or fishing communities.

[INSERT FIGURE 7-8 HERE
Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate $\pm$ SE.]

Warmer conditions may also allow range expansion of cropping activities polewards in regions where low temperature has been a past limitation (*low confidence*: *medium agreement, limited evidence*) provided varieties with suitable daylength response are available. This may particularly occur in Russia, Canada and the Scandinavian nations although the potential may be less than earlier analyses indicated due to increased climate extremes, water limitations and various institutional barriers (Alcamo *et al*., 2007; Dronin and Kirilenko, 2011; Kulshreshtha, 2011; Kvalvik *et al*., 2011; Tchebakova *et al*., 2011; Bindi and Olesen 2011). In many of these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due to lower rainfall, water shortages and high temperatures (*medium confidence: high agreement, limited evidence*).

Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and environments worldwide as high temperatures are known to reduce grain number, fill and quality (Challinor *et al*., 2009; Wassmann *et al*., 2009; Krishnan et al. 2007; Luo et al. 2009; Shimono et al. 2010; Stockle et al. 2010; Wassman et al. 2008) noting that a new cultivar usually takes between 8 and 20 years to deliver. Improving gene conservation and access to gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (e.g. Mercer et al. 2008, Wassman et al. 2008) as well as to take advantage of increasing atmospheric CO_2 concentrations (Ziska *et al*., 2012) and respond to changing pest, disease and weed threats with these developments needing **t**o be integrated with *in situ* conservation of local varieties (IAASTD 2009).

Similarly, the prospect of increasing drought conditions in many cropping regions of the world (e.g. Olesen et al. 2011) raises the need for breeding additional drought-tolerant crop varieties (Tao and Zhang, 2011; Mutekwa 2009, Naylor et al. 2007), for enhanced storage and access to irrigation water, more efficient delivery systems, improved irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water retention through practices such as minimum tillage and canopy management, increase in soil carbon and more effective decision support (Olesen et al 2011, Thomas, 2008, Falloon and Betts 2010, Luo et al. 2009, Lioubimtseva et al. 2009; Piao *et al*., 2010) amongst many other possible adaptations (e.g. WG II 22.4.3.7.1). Increasing soil organic carbon levels plays an important role for improved water retention and absorption capacity of soils (El-Hage et al. 2010; Smith and Olesen 2010). Several agricultural practices support increased soil carbon levels, such as use of organic fertilizers (compost, farm yard manure), crop rotations with deep rooting forage legumes or mulching of crop residues (e.g. Diacono and Montemurro 2010; Smith and Olesen 2010). Increasing soil carbon levels can also contribute to climate change mitigation (AR5 WG III). There is *medium confidence* (*high agreement, limited*

evidence) that crop adaptations can lead to moderate yield benefits under persistently drier conditions (about 10% from aggregation of studies (Challinor et al. 2013) and that irrigation optimisation for changed climate can increase yields by about 4% (Figure 7-8).

Diversification of activities is another climate adaptation option for cropping systems (Thornton *et al*., 2010; Lioubimtseva et al 2009). For example, Reidsma and Ewert (2009) found that regional farm diversity reduces the risk that is currently associated with unfavourable climate conditions in Europe. Diversification of activities often seeks to incorporate higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008). For future conditions, Seo (2010) assessed that under climate predictions for 2060, integrated crop-livestock farms could increase in number in Africa at the expense of specialized crop or livestock systems. The analysis indicated that the net revenue of the specialized farms could decrease by up to 75% compared with only 10% for the mixed farm but the nature and degree of change will in part depend on the specific climate changes. In some cases, increased diversification outside of agriculture may be favoured (e.g. Coulthard 2008, Mary and Majule 2009; Mertz *et al*., 2009a).

The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate change and increase the benefit of positive changes as found in AR4 (*high confidence: high agreement, medium evidence*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat, rice and maize (see Section 7.5.2). This meta-analysis adds more recent studies to that undertaken in the AR4 (Chapter 5). It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management increases approximately linearly with increasing temperature change being equivalent to about 15% of current yields for a temperature increase of 5ºC (Figure 7-9). This response is, however, extremely variable, ranging from negligible benefit from adaptation (even potential dis-benefit) to very substantial. The responses are dissimilar between wheat, maize and rice (Figure 7-5) and differ markedly between adaptation management options (Figure 7-8). For example, cultivar adaptation is assessed by several studies as providing substantially more benefit (mean of over 50%) than changing planting dates (13%) or optimizing irrigation to the new climatic conditions (4%).

[INSERT FIGURE 7-9 HERE
Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used.]

Potential increased variability of crop production means there is *high confidence* (*high agreement, medium evidence*) that other aspects of food systems such as food reserve, storage and distribution policies and systems may need to be enhanced (IAASTD 2009) along with a range of broader issues such as provision of effective insurance markets, clarity in property rights, building adaptive capacity and developing effective participatory research cultures that apply to more than just farming systems (Chapter 9, AR4 Chapter 5).

It is notable that most of the above adaptations raised above and used in this analysis are essentially either incremental changes to existing agricultural systems or are systemic changes which integrate new aspects into current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation benefits could be understated and a considerable opportunity cost may emerge (*low confidence: medium agreement, limited evidence*) (Challinor et al. 2013).

7.5.1.1.2. Livestock

Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk, and there is *high confidence* that this provides a sound starting point for climate change adaptation (*high agreement, medium evidence*). These adaptations include matching stocking rates with pasture production, adjusting herd and water point management to altered seasonal and spatial patterns of forage production, managing diet quality (using diet supplements, legumes, choice of introduced pasture species and pasture fertility management), more effective

use of silage, pasture spelling and rotation, fire management to control woody thickening, using more suitable livestock breeds or species, migratory pastoralist activities and a wide range of biosecurity activities to monitor and manage the spread of pests, weeds and diseases (Fitzgerald et al. 2008, Howden et al. 2008, Nardone et al. 2010, Ghahramani and Moore 2013, Moore and Ghahramani 2013). Combining adaptations can result in substantial increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and Moore 2013, Moore and Ghahramani 2013). In some regions, these activities can in part be informed by climate forecasts at differing time-scales to enhance opportunities and reduce risks including soil degradation (e.g. McKeon et al. 2009). Many livestock systems are integrated with or compete for land with cropping systems and one climate adaptation may be to change these relationships. For example, with increased precipitation, farmers in Africa may need to reduce their livestock holdings in favour of crops, but with rising temperatures, they may need to substitute small ruminants in place of cattle with small temperature increases or reduce stocking rates with larger temperature rises (Kabubo-Mariara 2009, Seo 2010, Thornton et al. 2010). As with other food systems there is a range of barriers to adaptation which could be addressed on-farm and off-farm by changes in infrastructure, establishment of functioning markets, improved access to credit, improved access to water and water management technologies, enhanced animal health services and enhanced knowledge adoption and information systems (Howden et al. 2008, Kabubo-Mariara 2009, Mertz et al. 2009).

Heat stress is an existing issue for livestock in some regions (*high confidence: high agreement, robust evidence*), especially in higher productivity systems (7.3.2.6). For example, some graziers in Africa are already making changes to stock holdings in response to shorter term variations in temperatures (Seo et al. 2008). Breeding livestock with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with productivity (Nardone et al. 2010) and so this option needs careful evaluation. Increased shade provision through trees or cost-effective structures can substantially reduce the incidence of high heat stress days (Nidumolu et al. 2011). In cooler climates, with warming there might be lesser need for winter housing and feed stocks.

7.5.1.1.3. Fisheries

The resources for capture fisheries are largely already fully or overexploited with an estimated 32 percent of stocks being overexploited and 53% being fully exploited (FAO 2010). Comparable global statistics are not available for inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas extraction, coastal zone development, land-based pollution and other activities are also negatively impacting status and production (WG II 30.6.7, Rosenberg and MacLeod 2005, Cochrane et al. 2009). For inland fisheries, overfishing is also widespread but the majority of impacts on the integrity of freshwater ecosystems and their resources originate from outside the sector (Welcomme et al. 2010). Climate change adds another compounding influence in both cases.

The vulnerability of fisheries and fishing communities to climate change will depend on their exposure to its physical and ecological effects, their dependence on the fishery and their sensitivity to physical effects, and their adaptive capacity (Allison et al. 2009). Adaptive responses to climate change in fisheries could include: management approaches and policies that strengthen the livelihood asset base, improved understanding of the existing response mechanisms to climate variability to assist in planning adaptation, recognising and responding to new opportunities brought about by climate change, monitoring biophysical, social and economic indicators linked to management and policy responses and adoption of multi-sector adaptive strategies to minimise negative impacts (WG II 6.4.2.1, Allison et al. 2009, Badjeck et al. 2010, MacNeil et al. 2010). A wide range of management tools and strategies have been developed to manage fisheries. However, Grafton (2010) points out that this array of tools is necessary but not sufficient for adaptation to climate change in fisheries. He argues that the standard tools for fisheries management were developed to control fishing mortality and to maintain adequate levels of recruitment to fishery stocks but without necessarily addressing the needs for resilience to change or to be able to function under changing climates. He therefore proposes that these conventional management tools must be used within processes that i) have a core objective to encourage ecosystems that are resilient to change and ii) that explicitly take into account uncertainties about future conditions and the effect of adaptation, and make use of models to explore the implications of these (Grafton 2010). There are also opportunities for fisheries to contribute to mitigation efforts

(Grafton 2010). Complementary adaptive responses include occupational flexibility, changing target species and fishing operations, protecting key functional groups, developing early warning systems for extreme events and the establishment of insurance schemes (Coulthard 2008, FAO 2009a, Daw et al. 2009, MacNeil et al. 2010, Koehn et al., 2011). Governance and management of fisheries will need to follow an ecosystem approach to maximise resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate induced change (FAO 2009a, Daw et al. 2009). Some adaptation options for tropical industrial tuna fisheries and coral reef fisheries are presented in Chapter 30, Section 30.6.1.1.

In contrast to capture fisheries, aquaculture is estimated to be the fastest-growing animal-food-producing sector and is outpacing human population growth. Per capita supply from aquaculture increased at an average annual growth rate of 6.6 percent from 1970 to 2008 (FAO, 2010). Adaptive responses in aquaculture include use of improved feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva and Soto 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert et al. 2009). Better planning and improved site selection to take into account expected changes in water availability and quality; integrated water use planning that recognises and takes into account the water requirements and social and economic importance of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water use in aquaculture operations are other adaptation options (De Silva and Soto 2009). Integrated water use planning will require making trade-offs between different land and water uses in the watershed (e.g. Mantua et al. 2010). De Silva and Soto (2009) also describe the need for insurance schemes accessible to small-scale producers so as to increase their resilience. In some near-shore locations there may be a need to shift property lines as the mean high water mark is displaced landwards by rising sea level (Huppert et al. 2009).

There are no simple, generic recipes for fisheries adaptation. Bell et al. (2011) suggest a list of 24 separate, but inter-related, actions that could be taken to adapt fisheries and aquaculture in the tropical Pacific to climate change. They break these management steps into three categories according to the primary objective: economic development and government revenue; maintaining the contribution of fish to food security; and maximising sustainable livelihoods. These authors also point out that actions and policies for adaptation in fisheries and aquaculture must complement those for other sectors. They suggest that the greater the number of different production systems to which communities have access, the greater the chance that some systems available to them will not be negatively impacted and that some may even benefit from climate change. Similar case-by-case, integrated planning will be required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.

7.5.1.1.4. Indigenous knowledge

Indigenous Knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability assured the source of food to hunters and reduced various risks (Ford 2009, Alessa 2008, Weatherhead et al. 2010), down to the southern Andes where the Inca traditions of crop diversification, genetic diversity, raised bed cultivation, agroforestry, weather forecasting and water harvesting are still used in agriculture (Goodman-Elgar 2008, Renard et al., 2011; McDowell and Hess 2012). In Africa, weather forecasting, diversity of crops and agropastoralism strategies have been useful in the Sahel (Nyong et al. 2007). Rainwater harvesting has been a common practice in Sub-Saharan Africa (Biazin et al. 2011) to cope with dry spells and improve crop productivity, while strategies from agropastoralists in Kenya are related to drought forecasting based on the fauna, flora, moon, winds and other factors (Speranza et al. 2010). In South Africa, farmer's early warming indicators of wet or dry periods in Namibia based on animals, plants and climate observations contributed to deal with climatic variability (Newsham and Thomas 2011). In the same way, in Asia and Australia IK plays an important role to assure food security of certain groups (Marin, 2010, Speranza et al. 2010; Biazin et al. 2012, Salick and Ross 2009, Kalanda et al. 2011; Green et al. 2010; Pareek and Trivedi 2011), although IK and the opportunities to implement it can differ according to gender and age in some communities (WG II 9.3.5.2.9, Rengalakshmi 2007; Turner and Clifton 2009, Kalanda et al. 2011) leading to distinct adaptive capacities and options.

However, because of changes already occurring in climate (seasonal changes, changes in extreme events: IPCC Extremes SR IPCC 2012) there is medium confidence that the reliance on IK could be reduced (Kalanda et al. 2011;

Speranza et al. 2009, McDowell & Hess 2012) affecting the adaptive capacity of a number of peoples globally (*medium agreement, medium evidence*). Moreover, there is *medium confidence* that some policies and regulations leading to limit the access to territories, promoting sedentarization, the substitution of traditional livelihoods, reduced genetic diversity and harvesting opportunities as well as loss of transmission of IK, may contribute to limit the adaptation to climate change in many regions (Nakashima et al. 2012) (*medium agreement, medium evidence*).

7.5.1.2. Practical Regional Experiences of Adaptation, including Lessons Learned

Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (see Section 7.5.2) additional to existing climate risk management. Where there have been management changes these have often been in response to several driving variables of which climate is only one (Smit and Wandel 2006, Mertz et al. 2009, Chen et al. 2011, Odgaard et al. 2011). More farmers express an intention to change rather than having implemented adaptive actions (Battaglini et al. 2009) although in some regions there appears to be adaptation to climate change that is happening now (Olesen et al. 2011, Fujisawa and Kobayashi 2010, Bohensky et al. 2012). Activities to build adaptive capacity to better manage climate change are more widespread (Twomlow et al. 2008) but there remain questions as to how this capacity will evolve and be maintained (Nelson et al. 2009). Crucial in this will be devolution of the decision-making process so as to integrate local, contextual information into adaptation decision-making (Nelson et al. 2008).

7.5.1.2.1. Observed and expected barriers and limits to adaptation

Adaptation is strongly influenced by factors including institutional, technological, informational and economic (WG II 14, WG II 15) and there can be barriers (restrictions that can be addressed) and limits in all these factors (WG II 16: *very high confidence: high agreement, robust evidence*). Several barriers to adaptation of food systems have been raised including inadequate information on the climate, climate impacts and on the risks and benefits of the adaptation options, lack of adaptive capacity, inadequate extension, institutional inertia, cultural acceptability, financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets and insurance systems (WG II 16, Bryan et al. 2009, de Bruin and de Link 2011, Deressa et al. 2009, Kabubo-Mariara 2009). Limits to adaptation can occur for example where crop yields drop below the level required to sustain critical infrastructure such as sugar or rice mills (Park et al. 2012). In some cases, these can be effectively irreversible. Some studies have shown that access to climate information is not the principal limitation to improving decision making and it can result in perverse outcomes, increasing inequities and widening gender gaps (Coles and Scott 2009). Incomplete adoption of adaptations may also occur.

Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock are assessed with *high confidence* as providing possible core adaptations of production systems (*high agreement, medium evidence*) (Mercer et al. 2008, Tingem and Rivington 2010) however, there is substantial investment needed to develop these along with delays before they are available, both of which can act as adaptation barriers. This may be addressed in part by investments to improve local crop varieties or livestock breeds that are easily adopted (IAASTD, 2009). There also can be physiological limits to performance such as upper temperature limits for heat tolerance (AR4 WGII 5.2.1).

7.5.1.2.2. Facilitating adaptation and avoiding maladaptation

Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain or perhaps to a broader community. However, there are possible maladaptations that arise from adapting too early or too late, by changing the incorrect elements of the food system or changing them by the incorrect amount. A key maladaptation would be one which increased emissions of greenhouse gases, this making the underlying problem worse (Smith and Olesen 2010; AR5 WGIII Chapter 11, *high agreement, robust evidence*). A recent review of agricultural adaptations however, has found that most categories of climate change adaptation options tend to reduce greenhouse gas emissions (Smith and Olesen 2010, Falloon and Betts 2010) (*medium confidence: medium*

agreement, medium evidence). These adaptations include measures that reduce soil erosion or reduce leaching of nitrogen and phosphorus, for increasing soil carbon, measures for conserving soil moisture and reducing temperature extremes by increasing vegetative cover.

There is a strong focus on incremental adaptation of existing food systems in the literature since AR4 (see above) however, and there is *medium confidence* that this may result in large opportunity costs that could arise from not considering more systemic adaptation or more transformative change (Kates et al. 2012; Howden et al. 2010) (*high agreement, limited evidence*). For example, in the USA, changes in farming systems (i.e. the combination of crops) have been assessed as providing significant adaptation benefit in terms of net farm income (Prato et al. 2010). There is a need to also engage farmers, policymakers and other stakeholders in evaluating transformative, pro-active, planned adaptations such as structural changes (Mäder, 2006; McCrum et al. 2009, Olesen et al. 2011). This could involve changes in land allocation and farming systems, breeding of functionally-different crop varieties, new land management techniques and new classes of service from lands such as ecosystem services (Howden et al. 2010). In Australia, industries including the wine, rice and peanut industries are already adopting transformative changes such as change in location so as to be early adopters of what are perceived as opportunities arising from change (Park et al. 2012).

There is substantial commonality in adaptation actions within different agricultural systems. For example, changing varieties and planting times are incremental adaptations found in studies of many different cropping systems as evidenced by the sample size in the meta-analysis. Collating information on the array of adaptation options available for farmers, their relative cost and benefit and their broad applicability could be a way of initiating engagement with decision-makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves which identify mitigation options, their relative cost and the potential size of emission-reductions (IPCC WG3). These curves can be used in setting investment priorities and informing policy discussions. The local nature of many adaptation decisions, their interactions with other highly contextual driving factors and the time and climate change-sensitive nature of adaptation decisions means however, that global, time-independent curves are not feasible. The studies in Figure 7-8 indicate that there some options which may be more relevant and useful to consider than others. These results however, illustrate the potential scope and benefit of developing effective crop adaptation options if implemented in an adaptive management approach.

7.5.2. Food System Case Studies – Examples of Successful and Unsuccessful Adaptation

Incremental, systemic and transformational adaptation to climate change is beginning to be documented, though the peer-reviewed literature largely covers vulnerability assessments and intentions to act, not adaptation actions (Berang-Ford et al. 2010).

Case 1: Incremental adaptation in the Sahel

Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other actions (Berrang-Ford et al. 2010, Speranza 2010), and in fact is usually a response to a complex of factors. This case, of the zaï soil management practice in the Sahel region, is an example where a complex of factors drives local actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the primary factors (Barbier et al. 2009, Mertz et al. 2010). Inherent poor soil quality and human activities have resulted in soil degradation – crusting, sealing, erosion by water and wind, and hardpan formation (Zougmoré et al. 2010, Fatondji et al. 2009). Zaï, a traditional integrated soil and water management practice, can combat land degradation and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits (20-40 cm in diameter and 10-15 cm deep) dug manually during the dry season and combined with contour stone bunds to slow runoff. A handful of animal manure or compost is placed in each pit. . By breaking the soil crust, the pits facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts termites, which have a positive effect on soil structure. The zaï technique is very labour intensive requiring some 60 days of labour per hectare. Innovations to the system, involving animal-drawn implements, can reduce labour substantially.

Case 2: Mixed farming systems in Tanzania

In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period. Intensification is under way, through change in crop choices, increased fertiliser use and irrigation, and especially greater labour inputs. Livelihood diversification has been the main adaptation strategy – this has involved more non-farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g. charcoal production), and has included artisanal gold and gemstone mining. Households have also altered their cropping systems, for example, by changing planting times. Migration is another frequently used strategy – with farmers moving to gain land, access markets or get employment. Parents also send children to cities to work for upkeep and cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity of households to cope. For instance, land cover change has negative impacts on future water supplies for irrigation, and deforestation and forest degradation means faltering forest-based income sources. This will be particularly problematic to the more vulnerable groups in the community, including women and children.

Case 3: Planning for adaptation in a CARE project

Anticipatory and planned adaptation has been initiated in many places, but it has been poorly documented in the peer-reviewed literature. In many cases these adaptation actions are the basis of externally-funded projects. For example, the humanitarian organization CARE is piloting an approach to increase the capacity of vulnerable communities to adapt to adverse climate change (Patt et al. 2009). In their project in Bangladesh they work directly with households to implement practical strategies to support adaptation to climate risk, as well as with local organisations to build their capacity to support communities to adapt. The initial stage in their work involves participatory assessments of vulnerability and adaptive capacity and perceived climate risk. In Bangladesh flooding, salinity, waterlogging and cyclones were the key challenges to be addressed. Given that vulnerability and adaptive capacity is gendered, the assessments were undertaken separately with men's and women's groups. The results of the assessments were then used to identify strategies to increase capacity to cope with the challenges, both present and those predicted under climate change. At the household level an example of an adaptation strategy that was taken up by households was the shift from raising chickens to raising ducks in light of increased flood risks. The work highlighted the difference in family responsibilities between men and women and differing vulnerability, and how this translates to differing priorities when planning for adaptation. Lack of mobility of women means that women have less access to information regarding potential hazards and possible adaptation strategies.

Case 4 Transformational change in the primary industries of Australia

Many of the cases identified in chapter 7 are examples of incremental adaptation; in many circumstances climate change may call for transformational changes in the agricultural sector, as incremental change will be insufficient (Howden et al. 2010). The primary industries in Australia are highly sensitive to the impacts of climate change and transformational adaptation is being considered and planned for (Park et al. 2012; Rickards and Howden 2012). Examples of transformational adaptations being implemented now include 1) relocation of parts of the rice and peanut industries to regions where future rainfall and irrigation water availability are anticipated to be more favourable causing major change in transport chains, inputs and management and, 2) the relocation of parts of the wine industry to cooler regions to offset risks of warming and forcing changes in supply chains through changes in grower contracts to increase the proportion of grape supplies from cooler regions with lower risk from high temperatures (Park et al. 2012). Researchers are working with those transforming to understand the processes needed so as to generalize and communicate them.

7.5.3. Key Findings from Adaptations – Confidence Limits, Agreement, and Level of Evidence

There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to changed temperature and precipitation will bring substantial benefit,(*high confidence: high agreement, robust evidence*) with some adaptations (e.g. cultivar adaptation) being more effective than others (e.g. irrigation optimisation) (7.5.1.1.1). Most studies have assessed key farm-level adaptations such as changing planting dates and associated decisions to match evolving growing seasons and improving cultivar tolerance to high temperature, drought conditions and elevated CO_2 levels. There is *medium confidence* (*medium agreement, limited evidence*) that

limits to adaptation will increasing emerge for such incremental adaptations beyond temperature changes of around 2ºC raising the need for more systemic or transformational changes (7.5.1, 7.5.1.2.2), An example of transformational change is latitudinal expansion of cold-climate cropping zones polewards but this may be largely offset by reductions in cropping production in the mid-latitudes due to rainfall reduction and temperature increase (*medium confidence: high agreement, limited evidence) (7.5.1.1.1).* Adaptations to food systems additional to the production phase have been identified and sometimes implemented but the benefits of these have largely not been quantified.

Livestock and fisheries systems also have available a large range of possible adaptations often tailored to local conditions but there is not adequate information to aggregate the possible value of these adaptations although there is *high confidence* (*high agreement, medium evidence*) that they will bring substantial benefit, particularly if implemented in combination (7.5.1.1.2, 7.5.1.1.3). Key livestock adaptations include matching stocking rates with pasture availability, water management, monitoring and managing the spread of pests, weeds and diseases, livestock breeding and adjusting to changed frequencies of heat stress and cold conditions (7.5.1.1.2). Fishery adaptations include management approaches and policies that strengthen the livelihood asset base, take an ecosystem approach to managing the resource and adoption of multi-sector adaptive strategies to minimise negative impacts. Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but not sufficient for adaptation to climate (7.5.1.1.3).

Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. There is *medium confidence* (*medium agreement, medium evidence*) that climate changes are reducing reliance on indigenous knowledge in some locations but also that some policies and regulation are limiting the contribution that indigenous knowledge can make to effective climate adaptation (7.5.1.1.4).

The focus on incremental adaptations and few studies on more systemic and transformational adaptation or adaptation across the food system mean that there is *medium confidence* (*high agreement, limited evidence*) that there may be underestimation of adaptation opportunities and benefits (7.5.1.2.2). In addition to this, there is a range of limits and barriers to adaptation and many of these could be addressed by devolution of the decision-making process so as to integrate local, contextual information into adaptation decision-making (7.5.1.2.2).

7.6. Research and Data Gaps – Food Security as a Cross-Sectoral Activity

Research and data gaps are seen mainly in the fact that most work since AR4 has concentrated on food production and not included other aspects of the food system that connects climate change to food security. Features such as food processing, distribution, access and consumption have recently become areas of research interest in their own right but only tangentially attached to climate change.

Other areas of neglect include food quality and nutritional aspects of climate change, the need to update and revise food production impact models, the need to create reliable, integrated food systems models at the regional and global scales geared to including climate change effects on the global food system.

In terms of crop production, important research questions are the extent to which CO_2 acts as a stimulant to crop growth, particularly in combination with other trace gases such as ozone. More attention needs to be given to the interaction between crop physiological thresholds in terms of high and low temperatures and drought and flooding. To date crop-climate models have not adequately included such thresholds and need to include them and examine their effects on crop yields and their quality under low and high levels of global warming. Excluding such features from models means that currently they may underestimate the impacts of global warming.

One of our conclusions from attempts to synthesise information on yield variation is that many studies either do not examine yield variability or do not report it. We recommend that closer attention is paid to yield variability, both for quantity and quality of food production, especially given observed price fluctuations associated with climate events. Within the context of yield variability, we expect environmental thresholds and tipping points, such as high temperatures, droughts and floods, to become more important in the future. Specific recommendations are food

production experiments in which changes in variability reflect predicted changes for given warming scenarios. Including such thresholds in models for high levels of global warming (i.e. 4-5 °C above pre-industrial) will very likely lead to reduced predictions of yield given changes in climate variability and increasing mean temperature. Research has also demonstrated that accurate crop productivity data would significantly improve future projections of yield. Important gaps in knowledge continue to be studies of weeds, pests, and diseases, including animal diseases, in response to climate change and how related adaptation activities can be robustly incorporated into food security assessments.

Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at a global or regional scale only and include adaptations to a limited extent. Increasing the resolution to forecast impacts and changes at the national and local ecosystem scale would provide valuable information to governments and stakeholders and enable them to prepare more effectively for expected impacts on food production and security.

The real contribution of inland fisheries and small-scale aquaculture to food security and nutrition is still poorly understood in many developing countries and regions and is probably frequently under-estimated. Research is required to determine the true contributions from these sectors and their vulnerability to climate variability and change to ensure that planning and implementation of adaptation gives due consideration to them and does not result in undesirable negative impacts on food security.

Currently, approximate estimates of the vulnerability of countries to climate change impacts on fisheries are available. Building on this start, further research is required to improve the accuracy of these estimates and to increase the resolution of the study to identify the most vulnerable zones and communities within countries for priority action in adaptation. There is considerable general information available on what adaptive strategies will be required where fisheries and aquaculture are expected to be impacted by climate change but there are very few case studies of actual adaptation or preparation for adaptation in practice. Implementation of case studies in a range of different social and ecological contexts would enable the existing theories to be tested and revised according to lessons learned.

Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to *ca*. 5ºC above pre-industrial but that the relative effectiveness of these often plateaus after about 3ºC. However, food security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in the food system especially when possible changes in climate variability are included .
From this chapter it is evident that since AR4, the production aspects of food production have continued to be studied much more comprehensively than the non-production elements of food security. Further studies require impacts and adaptation of global food security and systems in relation to global warming to be studied under a full range of radiative forcing scenarios and that these studies should be quantitative as possible. Such research should include climate impacts and adaptations of crops, livestock, fisheries, fruits and vegetables as production elements and processing, distribution and retailing and consumption patterns as the non-production but equally important elements of food security.

Frequently Asked Questions

FAQ 7.1: What factors determine food security and does low food production necessarily lead to food insecurity?
Observed data and many studies indicate that a warming climate has a negative effect to crop production, generally reduce yields of staple cereals such as wheat, rice and maize, which, however, differs between regions and latitudes. Elevated CO_2 could benefit crops yields in short term by increasing photosynthesis rates, however, there is big uncertainty in the magnitude of the CO_2 effect and that interactions with other factors. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification and through changes in the frequency, intensity and location of extreme events. Other aspects of the food chain are also sensitive to climate but such impacts are much less well known. Climate-related disasters are among the main drivers of food insecurity, both in the aftermath of a disaster and in the long run. Drought is a major driver of food insecurity, and contributes to a negative impact on nutrition. Floods and tropical storms also affect food security by destroying livelihood assets. The relationship between climate change and food production depends to a large degree on when and which

adaptation actions are taken. Other links in the food chain from production to consumption are sensitive to climate but such impacts are much less well known.

FAQ 7.2: How could adaptation actions enhance food security and nutrition?

Over 70 per cent of agriculture is rain-fed. This suggests that agriculture, food security and nutrition are all highly sensitive to changes in rainfall associated with climate change. Adaptation outcomes focusing on ensuring food security under a changing climate could have the most direct benefits on livelihoods, which have multiple benefits for food security, including: enhancing food production, access to markets and resources, and reduced disaster risk. Effective adaptation of cropping can help ensure food production and thereby contributing to food security and sustainable livelihoods in developing countries, by enhancing current climate risk management. There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times and crop cultivars and species. Adaptive responses to climate change in fisheries should include: management approaches and policies that maximize resilience of the exploited ecosystems, ensuring fishing and aquaculture communities have the opportunity and capacity to respond to new opportunities brought about by climate change, and the use of multi-sector adaptive strategies to reduce the consequence of negative impacts in any particular sector. However, these adaptations will not necessarily reduce all of the negative impacts of climate change, and the effectiveness of adaptations could diminish at the higher end of warming projections.

FAQ 7.3: How could climate change interact with change in fish stocks, ocean acidification?

Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of protein and some micronutrients. However, climate change will affect fish stocks and other aquatic species: increasing temperatures will lead to increased production of important fishery resources in some areas but decreased production in others while increases in acidification will have negative impacts on important invertebrate species, including species responsible for building coral reefs which provide essential habitat for many fished species in these areas. The poorest fishers and others dependent on fisheries and subsistence aquaculture will be the most vulnerable to these changes, including those in small-island developing States, central and western African countries, Peru and Columbia in South America and some tropical Asian countries.

Cross-Chapter Boxes

Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction

Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult; observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion

concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on

coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

CC-OA References

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Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water

management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use ($kWhr/m^3$) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.,* 2008, Bazilian *et al.,* 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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Table 7-1: Households divided into five categories of food access, indicating the impacts for them of food price increases.

Food Access Category	Characteristics	Impacts of food price increase on food access
Primarily subsistence (autarkic)	Subsistence farmers, herders, fishers and forest dependent populations; generally low share of population	Limited impact.
Food producers: net sellers	Generally lower share of population compared with net buyers (Aksoy and Sid-Dimelik, 2008; Zezza *et al.*, 2008; FAO, 2011)	Positive impact through increased income effect. Major beneficiaries are those with greatest surplus (e.g. larger, more commercialized farms).
Food producers: net buyers	Majority of poor rural households (IFAD, 2010; FAO, 2011)	Ambiguous: depends on relative size of income and price effects, but generally expected to be negative due to high share of income spent on food (Ivanic and Martin, 2008; FAO, 2011; Ivanic *et al.*, 2011)
Rural non-farming households	Rural landless: characterized by high rates of food insecurity; average share of population for 15 low income countries was 22% (Aksoy *et al.*, 2010).	Negative impact due to high share of income spent on food; however some limited evidence that wage increases may accompany price increases in which case overall effects are ambiguous (Aksoy and Sid-Dimelik, 2008; FAO, 2011)
Urban consumers	Growing share of population in most countries	Negative impact by reducing food affordability. Especially vulnerable to changes in global food prices, as they are more likely to consume staple foods derived from tradable commodities, whereas rural populations are more (FAO, 2008; Ivanic *et al.*, 2011).

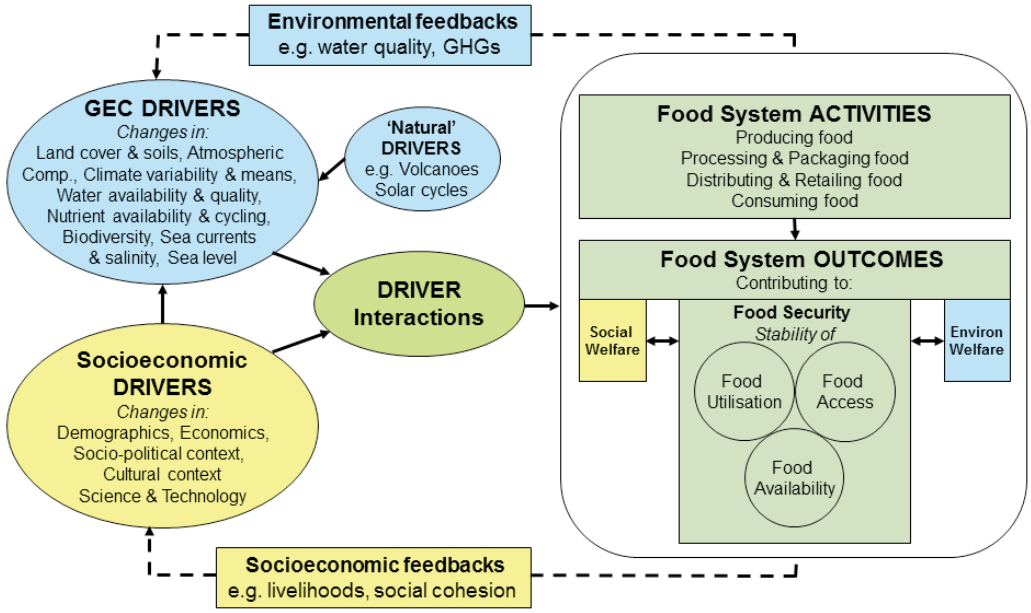

Figure 7-1: Main global environmental change (GEC) and socioeconomic drivers of food systems, the main food system activities, and the outcomes of these activities. The figure also shows the three main components of food security (circles), all of which need to be stable over time: Availability (with elements of production, distribution and trade); Access (affordability, allocation and preference); and Utilisation (nutritional value, cultural value and safety).

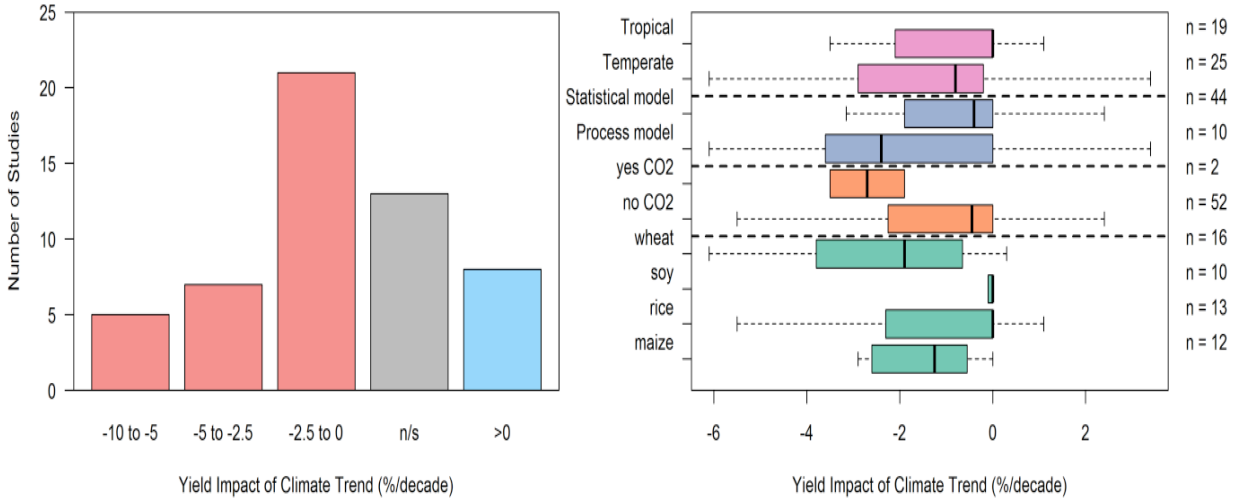

Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends (see 7.3.2.1.2) but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by temperate vs. tropical regions, modelling approach (process-based vs. statistical), whether CO2 effects were included, and crop. Studies were for China (Tao *et al.*, 2006; Tao *et al.*, 2008; Wang *et al.*, 2008; You *et al.*, 2009; Chen *et al.*, 2010; Tao *et al.*, 2012), India (Pathak *et al.*, 2003; Auffhammer *et al.*, 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell *et al.*, 2005), France (Brisson *et al.*, 2010), Scotland (Gregory and Marshall, 2012) Australia (Ludwig *et al.*, 2009), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al.*, 2010; Lobell *et al.*, 2011). Values from all studies were converted to percentage yield change per decade.

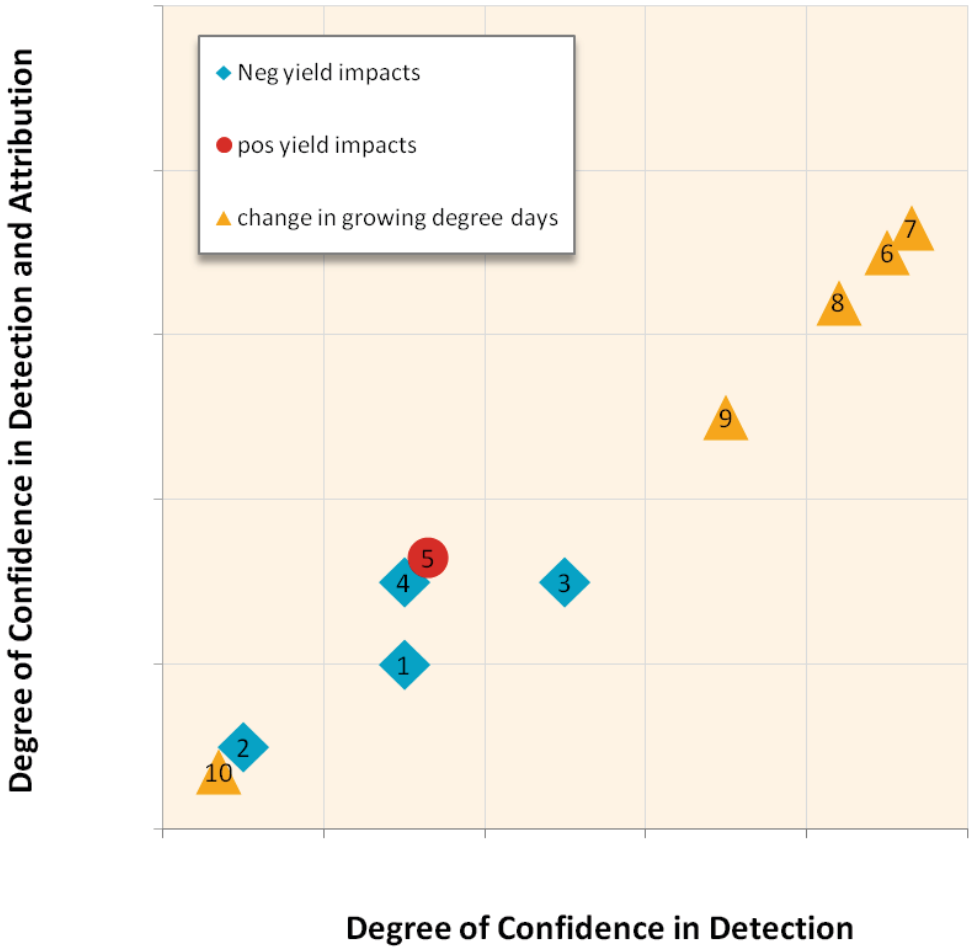

Figure 7-3: Confidence in detection and attribution of observed impacts on crop yields and growing season degree days. Yield impacts include both direct climate effects and effects of elevated CO_2, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010). Negative yield impacts: 1= Global maize , 2= Global wheat, 3= South Asia wheat; 4 = China maize and wheat; Positive yield impacts: 5 = UK wheat, sugarbeet, and potato. Increase in growing degree days: 6 = South Asia, main crops; 7 = China, main crops; 8 = Europe, main crops; 9 = Latin America, main crops; 10 = North America, maize and soybean. Yield impact confidence based on studies listed in Figure 7-2. Growing degree day confidence based on detection and attribution of trends in growing season temperatures (IPCC 2013, WG1, Chapter 10).

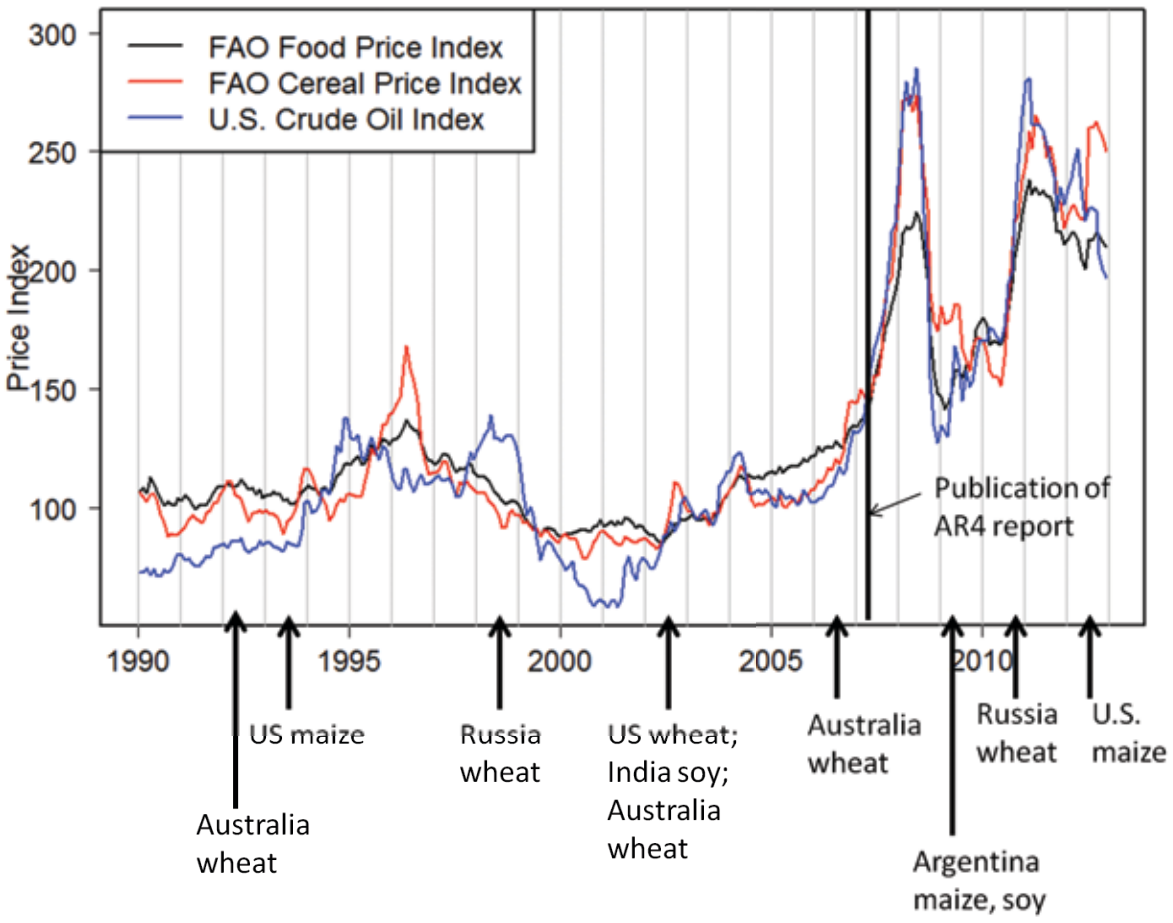

Figure 7-4: Since the AR4 report, food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index, along with events when a top 5 producer of a crop had yields 25% below trend line (indicative of a big weather effect). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years, perhaps reflecting the importance of interactions with global storage levels and rapid growth in crop demand. At the same time, because of increased biofuel demand, food prices are also increasingly linked to the price of crude oil, shown in the blue line (data available at http://www.eia.gov). Therefore, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002-2004 averages.

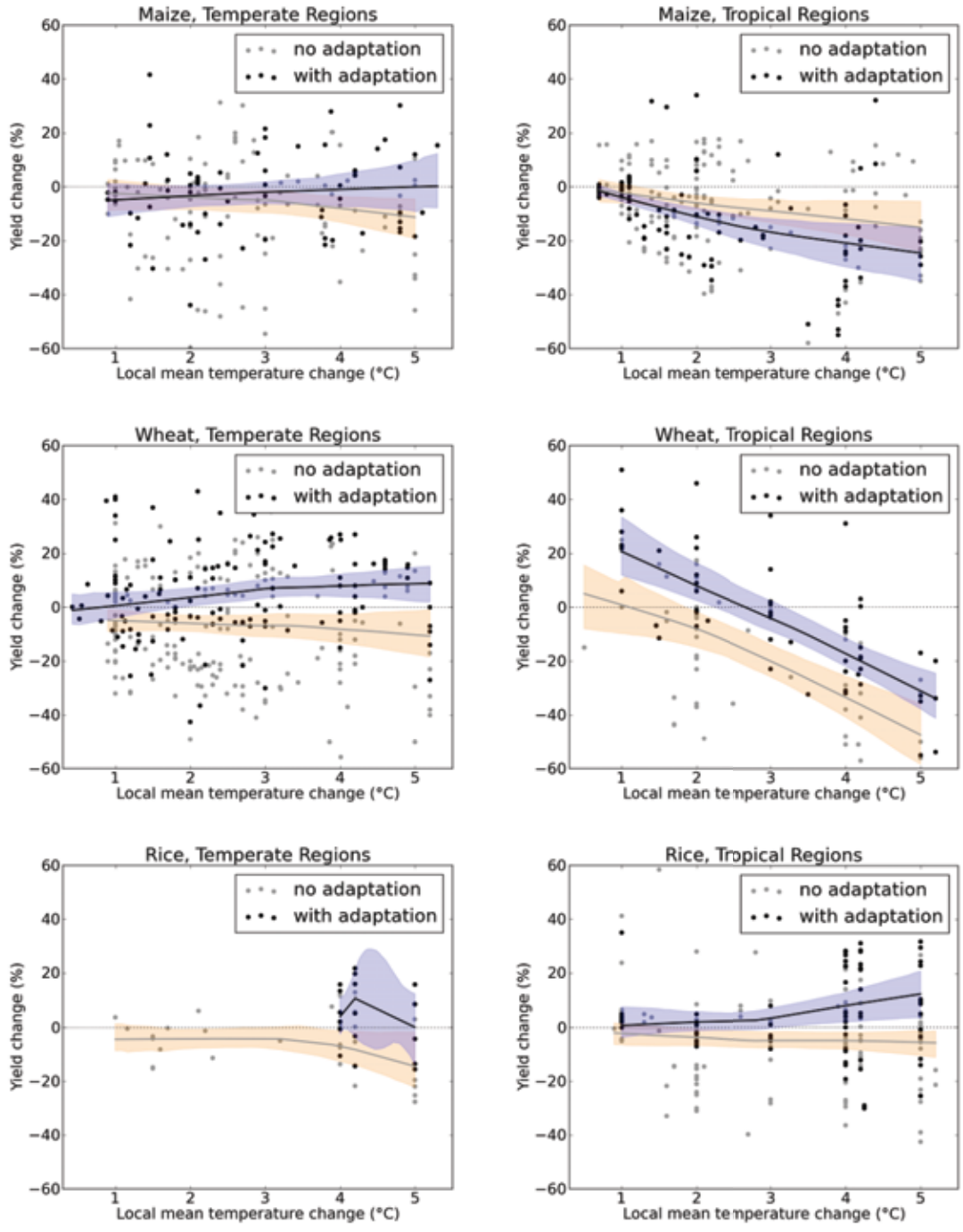

Figure 7-5: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated according to the presence (blue) or absence (red) of adaptation. Note that 10 of the 1125 datapoints across all six panels are outside the yield change range shown. These were omitted for clarity.

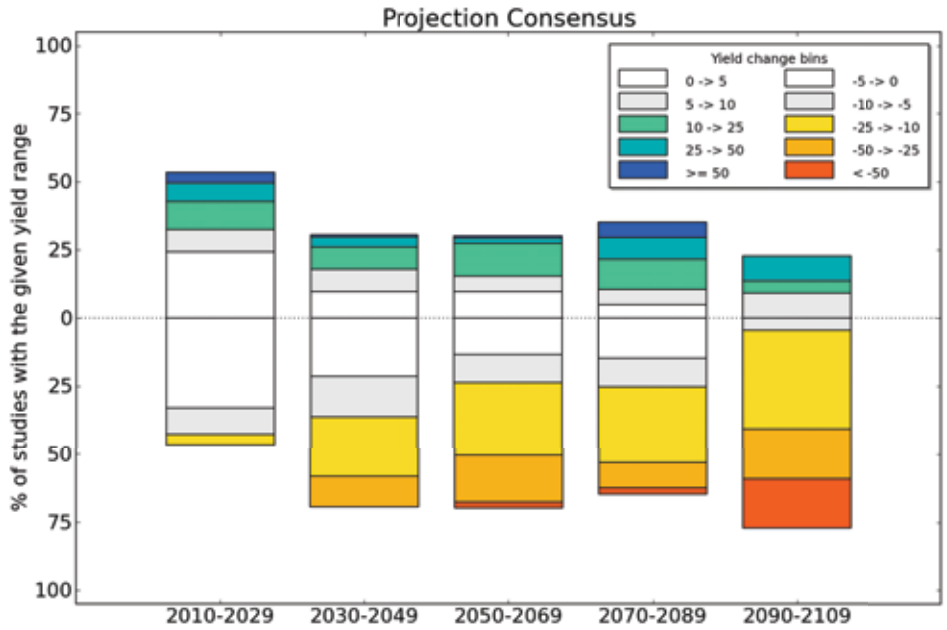

Figure 7-6: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Taken from (Challinor *et al.*, 2013).

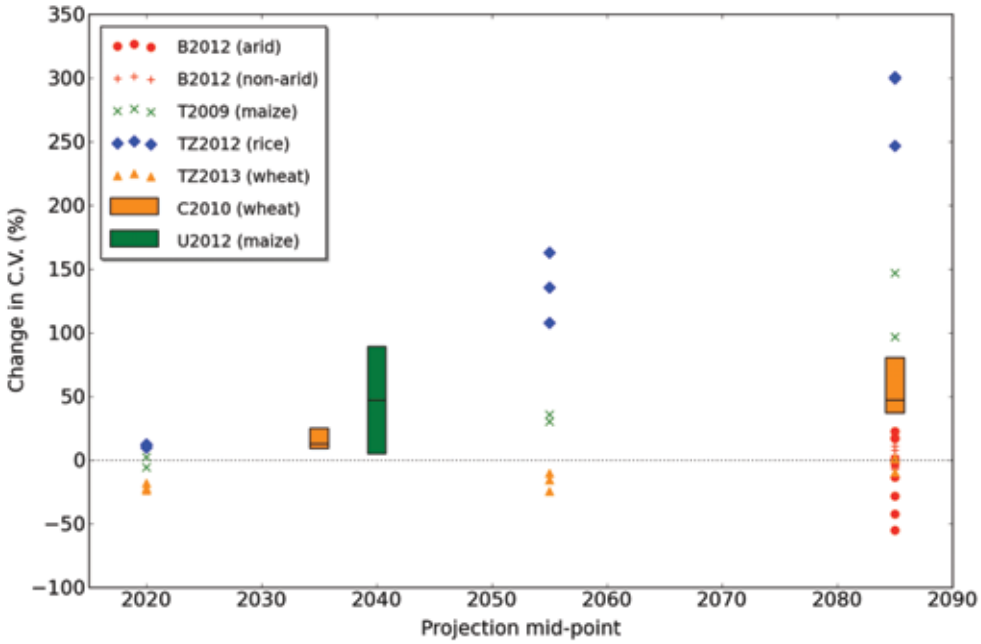

Figure 7-7: Projected percentage change in coefficient of variation (CV) for wheat (gold), maize (green), rice (blue) and C4 crops (red) taken from C2010 (Challinor *et al.*, 2010), B2012 (Berg et al., 2012), T2009 (Tao et al., 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban et al., 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies are for China.

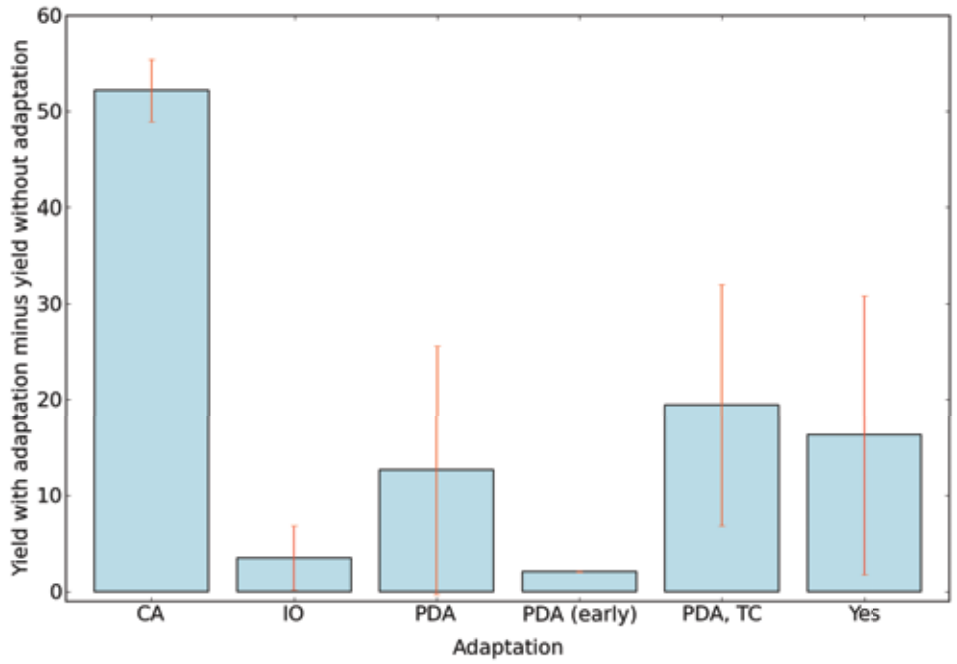

Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate ± SE.

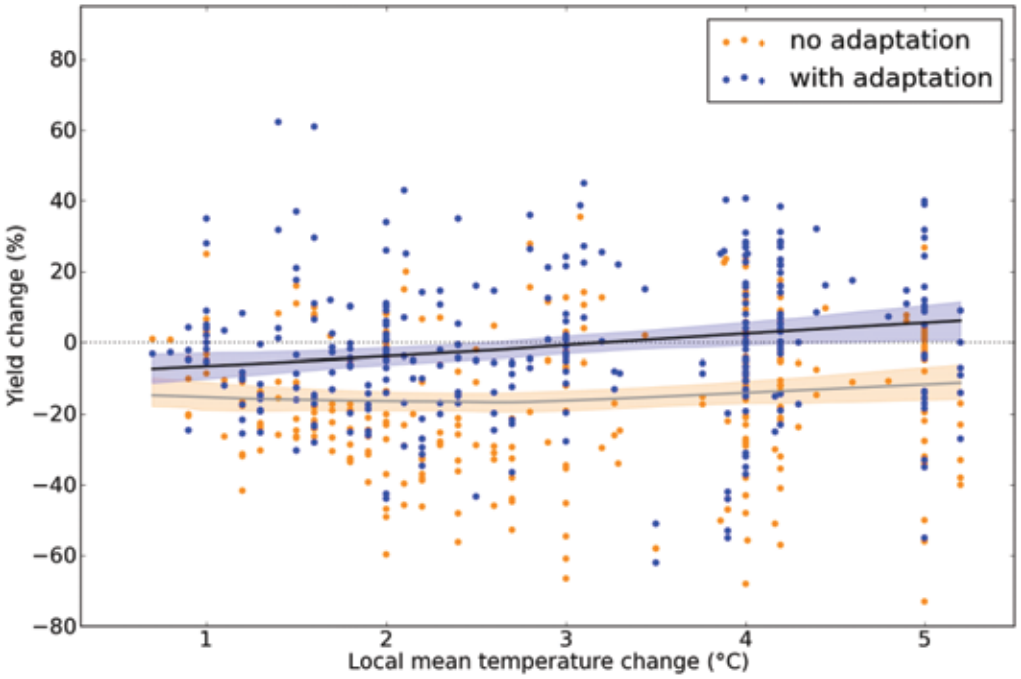

Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used.

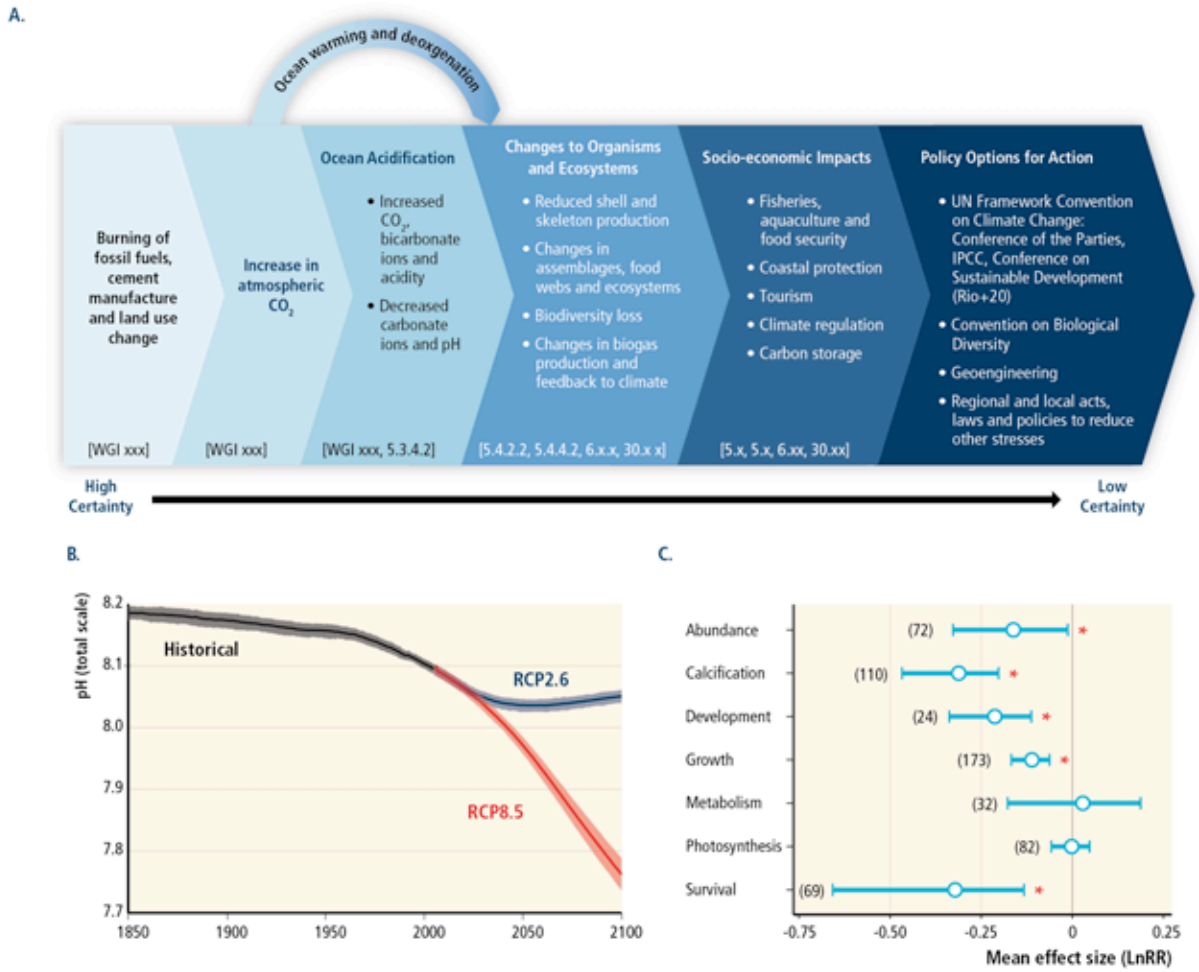

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

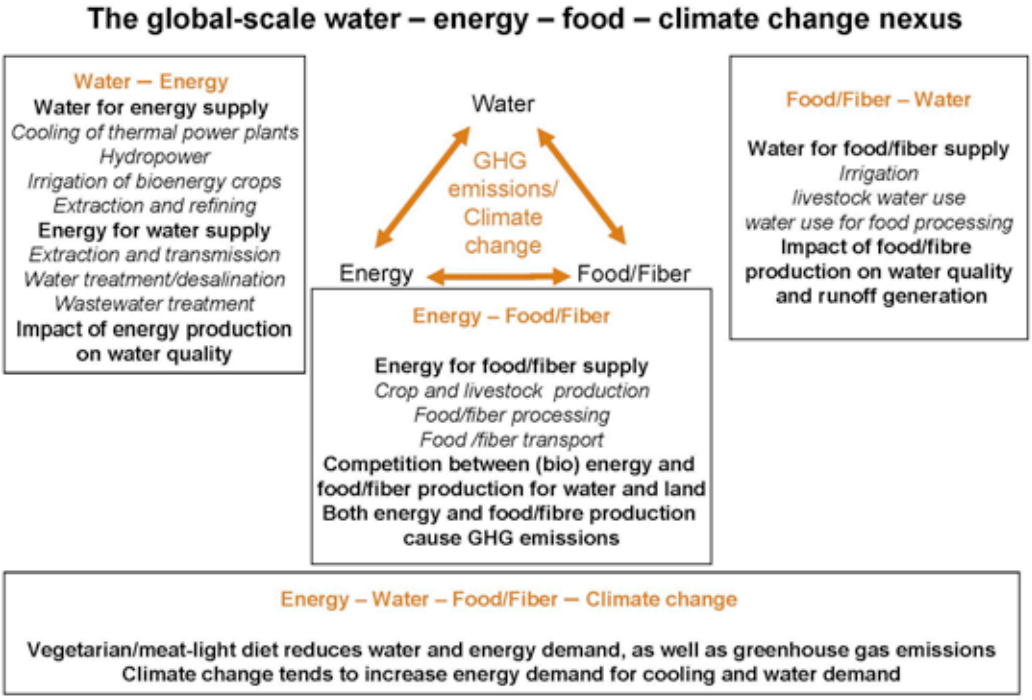

Figure WE-1: The water-energy-food nexus as related to climate change.

Chapter 8. Urban Areas

Coordinating Lead Authors
Aromar Revi (India), David Satterthwaite (UK)

Lead Authors
Fernando Aragón (Mexico), Jan Corfee-Morlot (USA / OECD), Robert B.R. Kiunsi (United Republic of Tanzania), Mark Pelling (UK), Debra Roberts (South Africa), William Solecki (USA)

Contributing Authors
Jo da Silva (UK), David Dodman (Jamaica), Andrew Maskrey (UK), Sumetee Pahwa Gajjar (India)

Review Editors
John Balbus (USA), Omar-Dario Cardona (Colombia)

Volunteer Chapter Scientist
Alice Sverdlik (USA)

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Frequently Asked Questions

8.1: How does disaster risk reduction relate to climate change adaptation?
8.2: Doesn't good development produce urban adaptation?
8.3: Wouldn't urban problems be lessened by rural development?
8.4: Shouldn't urban adaptation plans wait until there is more certainty about local climate change impacts?

References

Executive Summary

Successful global climate change adaptation depends centrally on what is done in urban areas (*high agreement, medium evidence*). Urban areas house more than half the world's population and concentrate most of its assets and economic activities. They also concentrate a high proportion of the population, and economic activities most at risk from climate change. In addition, a high proportion of global greenhouse gas emissions are generated by urban-based activities. Furthermore, projections for the next few decades suggest that it is in and around urban areas that almost all the increase in the world's population and much of the increment in capital formation, economic activity, infrastructure development, ecosystem degradation and emissions will take place. [8.1] Adaptation action in urban areas that delivers mitigation co-benefits is one of the most powerful and resource-efficient means of addressing climate change, as outlined in the AR5 Working Group III report.

There has been a very large expansion in the literature of relevance to climate change adaptation in urban areas since AR4 (*very high confidence*). [8.1] This includes documents prepared by many city governments and some international agencies on their initial responses to adaptation. There is also evidence of a greater interest in climate change adaptation from certain professions (including architects, engineers and urban planners and those working on disaster risk management). There is also a new literature underlining the importance of a shift in emphasis from urban adaptation to building resilience at city and regional scale. This will support the capacity to withstand unexpected impacts, flexibility, redundancy and planning for 'safe failure' in response to increasingly extreme climate adaptation as outlined in the AR5 SREX report. [8.1] Beyond this, an emerging literature is exploring urban transformations - adaptation that helps address the key drivers of anthropogenic climate change through combined processes of sound development, disaster risk reduction, increased resilience and ecosystem adaptation. [8.5] There is also some discussion of the adaptation limits that urban centres face and difficult decisions over what can be done that might include resettlement or abandonment of previously developed land. [8.3]

Cities are complex inter-dependent systems with potential synergies that could be leveraged to support climate change adaptation (*high agreement, low evidence*). In many cities, adaptation effectiveness is constrained by complex inter-dependencies – for instance the impact of power failures or fuel shortages on water supplies, drainage, transportation, telecommunications and health care services. There is also the dependence of emergency services on all-weather roads, functioning communications systems and robust health care centres and the dependence of urban populations and economies on food and resources from beyond their boundaries. [8.2] A few cities have adaptation initiatives underway for energy systems or are considering what steps are needed to do so; energy policy discussions in the past have been dominated by mitigation concerns. [8.3] Urban enterprises developed within globalized systems of production depend on reliable supply chains which may face particular difficulties. [8.3] Conventional infrastructure investment decision-making may be interventionist or reactive and overlook more open-ended and flexible concepts such as adapting well, climate smart, sustainable adaptation and resilience. [8.5] Thus raising urban adaptive capacity in the context of climate change requires effective multi-level governance (so all levels of government work together) with institutions that facilitate coordination across multiple, nested and poly-centric authorities and have the capacity to mainstream adaptation measures. There are synergies to be encouraged in peri-urban or nearby rural areas where land-use management around a city supports rural livelihoods and protects ecosystem services. [8.3] This is yet to be built in most parts of the world. [8.4, 8.5]

The scale and concentration of urban climate risk and hence the imperative for adaption are better acknowledged now but poorly understood and rarely acted upon (*medium confidence*, characterized by *high agreement* and *medium evidence*). Increasing concentrations of population, assets and economic activities in the urban areas of almost all countries, irrespective of income-level will increase the concentration of climate-related risks for a large and growing proportion of the world's population. [8.1] This could threaten economic and development processes, poverty reduction and ecological sustainability. Awareness of these emergent risks is growing, but responses are weak except for a handful of cities largely in high-income countries. [8.3, 8.4] Three identifiable strategies to enable urban adaptation are: awareness building, evidence-based analysis and action at the appropriate level. [8.4] Most current adaptation action focuses on low-cost interventions such as infrastructure and asset-creation as a co-benefit of existing development interventions. The weak emphasis on human, institutional and ecological adaptation with long-term resilience building potential is a matter of concern. [8.5, 8.3]

Rising sea levels, associated coastal and riverbank erosion and flooding in conjunction with storm surges could all lead to widespread impacts on populations, property and coastal vegetation and ecosystems, and threats to commerce, business, and livelihoods (*very high confidence*). Sea-level rise represents one of the primary shifts in urban climate change risks, given the large and often increasing concentration of urban populations in coastal locations. [8.2] Coastal cities with extensive port facilities and large scale industries in low-elevation coastal zones including petro-chemical and energy related industries are vulnerable to climate change related increased flood exposure. [8.2] Many cities in Asian high growth economies are located on low-lying coastal areas, which are undergoing rapid urbanand economic transformation. Without adaptive measures and with rising concentrations of population, infrastructure, and industries along these coasts, there could be a non-linear increase in coastal vulnerability over the next two decades. [8.3] Many cities and smaller urban centres already experience large floods regularly and will be at greater risk of flooding if rainfall intensities increase. This in turn could lead to the destruction of properties and public infrastructure, contamination of water sources, water logging, loss of business and livelihood options and increase in water related diseases as noted in wide range of studies. [8.2]

Climate change can influence the dynamics of city microclimates while cities can alter a localized region's climate (*high confidence,* based on *high agreement* and *high evidence*). The dense nature of many large cities, high energy consumption, and regional climate conditions produces pronounced influences on anthropogenic heat emissions. [8.2] Reviews of megacity impact on air flow indicate that megacities, especially coastal cities, influence both internal city environmental and regional weather and air quality. [8.2] Additional environmental impacts have also been observed, such as increased levels of surface run-off. Other coupled processes includethe effect of microscale to mesoscalechanges in the built environment on Urban Heat Islands (UHI) thereby impacting mesoscale processes such as land-sea breeze effect and katabatic winds, inturnmodifyingthe spatial extent and magnitude of local urban climate change impacts resulting from radiative forcing. [8.2]

Increasing city resilience to climate change, building adaptive capacity and adequate resourcing could enable cities to 'bounce forward' (*medium confidence*, supported by *high agreement* and *low evidence*). Effective multi-level urban risk governance, alignment of multiple (potentially conflicting) policies and incentives, early and appropriate adaptation choices and implementation action could increase city resilience to climate change and build needed local and regional adaptive capacity. This would strengthen development processes, limit maladaptation, support more effective adaptation and build positive synergy with climate mitigation measures. This combined with strengthening of local ecological and built infrastructure and services, better integrated urban and adaptation planning, strengthened local government and community adaptation capacity, synergy with the private sector and appropriate financing and institutional development could enable cities (especially in low- and middle-income countries) to use their limited resources to 'bounce forward' rather than respond in a fractured, ad-hoc and poorly-resourced manner to existing or impending climate risks. [8.4, 8.5] "Bouncing forward" is enabled by building transformatory adaptive capacity and climate resilience through a mix of sound development, disaster risk reduction, and ecosystem-based adaptation rather than 'end-of-the-pipe' or incremental adaptation interventions.

Sound development is a necessary, but not sufficient condition to enable urban climate resilience (*medium confidence*, supported by *high agreement* and *medium evidence*). There is a widespread assumption that sound urban development, especially universal provision of basic infrastructure and services (piped water, provision for sanitation and drainage, solid waste collection, health care, schools, emergency services, policing) are sufficient to

enable urban resilience to climate change, based on the perceived experience of some high-income nations. [8.2] These provide an important base from which to build resilience. The importance of harmonization and synergy of climate adaptation and mitigation with poverty reduction, livelihood development, food security, universal access to adequate housing and basic services and disaster risk reduction is slowly being understood. But this is a complex terrain that needs more evidence and experimentation to gauge the effectiveness and limitations of current models of infrastructure and service provision – including 'social capital'-based and community-led climate adaptation and acceptance of this among national governments and mainstream development agencies. [8.3, 8.5]

City-based disaster risk reduction is a strong foundation around which to build urban climate resilience (*high confidence*, based on *high agreement* and supported by *medium evidence*). Many urban areas have long been exposed to a range of hazards and disaster risks that could be exacerbated by climate change: water shortages and droughts in urban regions, geo-hydrological hazards, inland and coastal flooding, windstorms and storm surges, high levels of air pollution, extremes in urban heat and cold and urban heat islands and novel compound and slow onset hazards that impact ecosystem resilience. [8.2] Experience in effective city-level disaster risk reduction to address these challenges largely by vulnerability reduction and exposure modification, has been built in many cities across over the last few decades via local hazard, risks and vulnerability studies and interventions. Some national governments have set up frameworks and financing mechanisms to support local government and civil society implement disaster risk reduction. This is a valuable foundation for climate change adaptation but it will need to also take account of how hazards, risks, slow onset impacts and vulnerabilities change over time and thereby seek to converge development and disaster risk reduction policies, institutional development and investmentmobilisation to meet short- to medium-run risk reduction and longer-term urban adaptation goals. [8.3]

Urban concentration and agglomeration economies can be a strategic asset in climate adaptation action (*medium confidence*, based on *medium agreement* and *low evidence*). Many of the challenges and opportunities for urban adaptation come from the concentration of people and enterprises in locations of high risk. There are agglomeration economies for much of the infrastructure and services for climate change adaptation but they need to be acted on. There is *high agreement*, supported by *high evidence*, that many urban centres are on sites that face high levels of risk with risks exacerbated by built and ecological infrastructure deficits. Many cities in low- and middle-income nations have a high proportion of their population in informal settlements that lack risk-reducing infrastructure and services and that are located on floodplains, alongside rivers, in areas prone to slips and rockfalls or on steep unstable slopes. These sites are settled because their residents cannot afford housing on safer sites. Where local governments are unable or unwilling to act on these, population concentration brings disadvantages. [8.2, 8.3] This has been seen as an argument to incentivize adaptation-led relocation but that can cause very large disruptions to both residents and economic activity. [8.2] Urban agglomeration economies are often discussed in regard to enterprises. Cities may represent a particular centre of interest for private sector engagement around climate change partly because they concentrate large infrastructure investments and related business. [8.4] There are potential urban agglomeration economies around cost-effective adaptation and resilience building via improved built and ecological infrastructure and services and bringing together people, communities and institutions to respond collectively to climate change risks. [8.3] There is also the need to take recognize potential conflicts between the adaptation and mitigation agendas, as well as the establishment of locally specific limits to adaptive interventions. [8.5] The "density conundrum" where increased urban densities could enhance climate mitigation potential can limit the possibilities of ecosystem based adaptation, cross thresholds of acceptable biodiversity change and may exacerbate urban heat island risk. [8.3]

Building climate resilience in cities can be well-served by ecosystem-based adaptation with water and food systems as foci (*medium confidence*, based on *high agreement* among practitioners and *medium evidence*). Ecosystem-based adaptation is regarded as one of the morecost-effective and sustainable approaches to urban adaptation, although the costs of needed land acquisition can be high. [8.5] This is even though climate change will impact ecosystem services by altering ecosystem functions such as temperature and precipitation regimes, evaporation, humidity and soil moisture levels. Ecosystem-based adaptation is closely linked to sustainable water management ensuring sufficient supplies, increased capacities to manage reduced freshwater availability, flood risk reduction, managing waste water flows and ensuring water quality. [8.3, 8.5] There are considerable knowledge gaps in determining the limits or thresholds to adaptation of various ecosystems and where and how ecosystem based adaptation is best integrated with other adaptation measures. [8.5] There is *high confidence* that urban food-

adaptation is linked to progressive public policy on food security and livelihood development; addressing constraints in agricultural production and food supply chains and limiting food price shock impacts caused by extreme eventson the food and nutrition security of low-income groups. [8.3]

Good quality, affordable and well-located housing provides one of the bases for city-wide adaptation to climate change (*high confidence*, supported by *high agreement* and *high evidence*). Climate change adaptation in urban centres will be built on the bedrock of good quality and affordable housing that conforms to appropriate health and safety and climate-resilient building standards and has sufficient residual structural integrity over its service life to protect its occupants against extreme weather, especially heat waves and storms. Good quality housing should provide its occupants with a comfortable, healthy and secure living environment and protect them from injuries, losses and damage. This requires effectiveland-use planning and regulation to control development in flood-prone and other high risk areas. It is particularly important for vulnerable groups especially children and older residents with chronic health conditions. This can be enabled via a range of structural interventions, interventions that reduce risks to housing and support access to quality housing for low-income groups, non-structural interventions (like insurance) and disaster risk reduction measures. Well-coordinated strategies are required to address a multiplicity of agencies working at various levels, overlapping regulation and lack of committed resources. [8.3]

Reducing basic service deficits and building resilient infrastructure systems could significantly reduce global climate risk (*very high confidence*, supported by *high agreement* and *high evidence*). Around one billion people live in informal settlements in urban areas with inadequate or no provision for infrastructure and services that provides a foundation for adaptation. Here, poverty and social inequality may be aggravated by climate change and the lack of adaptive capacity. The adaptive capacity of an urban centre is much influenced by the quality and coverage of infrastructure (piped water supplies, sewers or other forms of provision for sanitation, drains, all weather roads and electricity provision) and services that include solid waste collection (vital for keeping drains functioning), policing, health care, emergency services and measures to reduce disaster risk. The extent to which urban and higher levels of governments are able to mobilize resources, choose the most appropriate technical and institutional systems for service delivery influences adaptive capacity and deepens climate resilience. [8.3] The rate and magnitude of urban development in some low- and middle-income countries also brings great challenges that many high-income nations do not have to deal with.

Urban governments are the fulcrum of successful urban climate adaptation (*high confidence*). Local governments are responsible for many of the needed measures for climate change adaptation in urban areas. This makes sense since most risks and vulnerabilities are rooted in local contexts and much of the risk reducing infrastructure and services are within their jurisdictions. [8.3] The incorporation of climate change adaptation into each urban centre's development planning and investments is well served by an iterative process of learning about changing risks and opportunities and drawing in different stakeholders, to inform a balanced assessment of policy options and decisions. Engagement with local stakeholders, built upon openness and transparency about climate change information and its risks, can ensure the needs and priorities of low-income and vulnerable groups get attention and that the private sector is brought into discussions. The role of urban governments in climate adaptation is now more widely recognized, but in many nations, local governments need a stronger financial and institutional base to be able to act on this, including land use management and infrastructure investment. [8.4] Operationalisation will also need a redirection of current priorities, investment and capacity building plans including those that strengthen the investment capacity of urban, city and metropolitan governments. [8.2, 8.3]

City governments are slowly learning from climate change adaptation implementation experience (*medium confidence*, based on *high agreement* and *medium evidence*). The last five years have brought many examples of city governments assessing urban adaptation needs and responding. [8.3] These have often included the designation of a unit within city government with responsibility for adaptation, measures to involve key sectors so they understand why they need to engage with adaptation, the importance of local champions to initiate measures and ensure continuity and the importance of dialogue and discussion with all key stakeholders. [8.4, 8.5] There is also recognition of the need to review building codes, the climate data on which the codes are founded, infrastructure standards and land-use management thereby developing scalable approaches to local adaptation planning. [8.3] City governments that have taken adaptation seriously have drawn in other institutions for support, including local universities and research centres and representative organizations of those living in informal settlements. [8.4]

Effective ways to engage local government attention have been the demonstration of climate change adaptation's importance for a city's continuing economic success, improved service delivery, job creation and risk management. [8.5]

The process of city-based climate adaptation learning is slow, complex and fraught with multiple interlinked challenges (*very high confidence*). Although some city governments have developed innovative adaptation plans, the scale and scope of what is needed is still poorly appreciated. Multiple changes across legal and regulatory frameworks, jurisdictions, policies and intergovernmental flows are needed to mainstream urban climate adaptation. These can be slow to be accepted and slower to implement. The capacity to integrate climate risk, disaster risk reduction, urban infrastructure and planning are being slowly built in some parts of the world. Sector policies need to take account of climate change. Many such policies will require changes to prevent increases in the vulnerabilities of urban populations, infrastructure and natural systems. In most urban centres, these include policies on water, wastewater, solid waste, natural resource management, building regulations, land-use management, transport planning, and disaster management. [8.4] Other challenges that need addressing include: reducing the lack of clarity of multi-level governance mandates; addressing the tension between local and higher-level and sometimes international agency driven priorities; the competition that long-term climate adaptation horizons will face from short-cycle electoral processes, a focus only on growth and competitiveness and local short-run priorities; overcoming the lack of human and financial resources and compartmentalisation and fragmentation of urban government. An openness to emergent and uncertain climate risks via awareness and institutional development can bridge the gap between the need for phased adaptation interventions and the many years it would take for their benefits to become visible. [8.3, 8.4, 8.5] The practice of effective monitoring of development and of the implementation of adaptation plans is still evolving, given the localized nature of most urban adaptation action. [8.5]

Locally-relevant adaptation plans, data and feedback mechanisms are important for building urban climate resilience (*high agreement* and *medium evidence*). Governments, households and the private sector need relevant, reliable local information, including climate projections, to encourage them to act and inform their actions. Despite growing attention, much-needed information and assessment of climate change at urban spatial scales is generally still lacking. Unlike mitigation planning, adaptation programmes are less open to a standard set of requirements, given that actions are oftenrooted in local circumstances, involve multiple stakeholders, are cross-sectoral, multi-scalar and multi-synchronous, and include a high level of uncertainty. [8.5] Only a small number of cities, largely in high-income countries, have quantified risks in local contexts and even fewer have quantified possible costs of climate change risks under different climate and/or socio-economic scenarios. First and second order impacts such as sea level rise and coastal and riverine flood risk and health and water resources are among the most studied sectors, while third order impacts on energy, transport and built infrastructure receive far less attention, and yet these sectors are often targeted for mitigation-focused interventions. While science and climate change information is increasingly available, socio-economic drivers of vulnerability and impacts, such as an increasing health risk and disease burdens are less well understood. [8.2, 8.4] Tools for risk screening and management, which draw on detailed data and projectionsboth from physical science and the socio-economic domains, can help engage the interest of local governments, businesses and civil society organizations. They can also help the translation into information useful for decision-making. City experience is slowly developing around multi-stakeholder adaptation engagement and awareness generation to build broad based support; mainstreaming climate adaptation processes into municipal planning, land use management and building and infrastructure codes. Improved feedback, monitoring and reporting capacity supported by new generation risk screening, vulnerability mapping and integrated urban climate assessment tools are helping catalyse social-learning to help mainstream climate adaptation into urban policies and planning. [8.4] Assessment tools such as scenario-planning that go beyond spatial and multi-criteria assessment to consider the urban environment as a system to better understand the inter-connections, cascading impacts and vulnerabilities are also recommended [8.4, 8.5)]

Enabling the agency of low-income households and vulnerable communities is a powerful adaptation strategy (*high confidence*). Informal settlements in low- and middle-income nations are among the largest existing and emerging concentrations of climate vulnerable urban populations, assets, infrastructure and ecosystem services. [8.1, 8.2, 8.3] Many urban governments are unable to extend a full range of entitlements, services and the institutional support necessary for effective adaptation to these settlements. For most cities and smaller urban centres in low- and middle-income nations, poverty reduction needs more attention because of the strong association between poverty

and environmental health, disaster and climate change risks. [8.5] In many high climate risk locations, community and household-led adaptation have intervened with their limited resources to fill this gap. In informal settlements, engagement with community learning provides a means for participatory community risk assessment, where local capacity to adapt is built in part through accessing their knowledge. The scale and range of what this can achieve is increased with local governments' support; simply shifting the burden of adaptation to the community level is unlikely to bring success. [8.4] It is now more common for local and national governments to work with the inhabitants of informal settlements to install or upgrade infrastructure and services and address insecure tenure; this can strengthen social capital creation processes and build their resilience to climate change impacts. [8.4] Enabling community-led adaptation can be challenging and depends on a number of factors including representativeness of leadership, supportive local governance, community organizations' ability to pressure government and other stakeholders to respond to their concerns, as well as a recognition of the limits of community-based intervention. [8.4, 8.5]

Effective local action requires coordinated support from higher levels of governments and other stakeholders (*medium agreement* supported by *medium evidence*). To be effective adaptors, urban governments need a mandate around climate change adaptation via supportive policy and enabling legislative frameworks from higher levels of governments (including national, supra-national and state/provincial levels). Universities and research institutions, multilateral and bilateral agencies, financial and insurance and other private sector agencies have successfully assisted urban governments and households to mobilize around climate adaptation. Since effective adaptation for urban centres needs local responses and includes major roles for local governments and civil society (especially those representing those most at risk), consideration needs to be given to mechanisms by which international support for adaptation can work at scale while supporting local processes [8.4, 8.5] Large metropolitan areas and their rapid growth raise the level of complexity of managing adaptation, requiring action to be coordinated across multiple urban jurisdictions. The role of local government champions has often proved critical in providing initial leadership towards promoting and sustaining an adaptation agenda. [8.5] Although there is some evidence of innovative responses at the sub-national levels to plan for extreme weather events and climate change, limited local government capacity and experience suggests a need for support from higher levels of government. [8.4] A phased approach, whereby the most urgent matters, such as rapid-onset disasters, are prioritized first, leaving a longer time period to plan for slow-onset impactswhich may be associated with greater uncertainty, is most likely to attract local government attention. [8.5]

Building human and institutional capacity for urban climate resilience will accelerate implementation and improveoutcomes (*high confidence*). A binding constraint to effective and timely urban adaptation and building resilience is effective institutions and leadership across government, communities, civil society, knowledge institutions and the media. This can be addressed by a number of structural interventions to enable city-wide alliances and frameworks to be built, institutionalization of processes, building a culture of exchange between learning organizations and a strong emphasis on capacity building. [8.4] The locus of the climate change focal point in government has a strong bearing on its success. There is evidence of expanding urban adaptation leadership, but building a wide support base for adaptation across many sectors, in and outside of government to de-risk the impact of slow institutional development and leadership change is an important priority. Local or regional boundary organisations such as nearby academic or research communities have been shown to have influence and support policy decisions. Networking and sharing experiences among adaptation practitioners and between cities is also an important vehicle to improve city-level outcomes. [8.4, 8.5]

Adapting urban centres' economic base can enhance comparative advantage, deepen climate resilience and limit disadvantage (*high agreement*, supported by *medium evidence*). Climate change will shift the comparative advantages of cities and regions and differentially threaten or enhance the resource, asset and economic base and so lead to significant structural changes and impacts on local, national and potentially the global economy. Effective adaptation can protect a city's economic base via a mix of strategies. These include extreme weather exposure reduction via effective land-use planning, selective relocation and structural measures; reduction in the vulnerability of lifeline infrastructure and services (water, energy, waste management, food, biomass, mobility, local ecosystems and telecommunications) and measures to assist vulnerable sectors and households; mitigation of business interruption and capital stock losses and support to the 'waste economy' and the 'green economy'. These may be easier and cheaper to implement in new and peri-urban developments. [8.3]

There is limited commitment to and development of urban climate adaptation finance (*high agreement* and *low evidence*). Available finance for urban adaptation span domestic and external public and private sources. Domestic public funding can be raised through a variety of measures ranging from urban fiscal policies (where there is capacity to do this) to revenue transfers from national (and often provincial or state) government. External public funding can come from traditional development finance sources (i.e. multilateral development banks and bilateral development co-operation partners). The need for urban adaptation investments will far exceed available public funding. Smaller cities and other urban centres with weak and fragmented governance structures may be least equipped to access available climate change funding, even as they house some of the most vulnerable populations. Domestic private investment by individuals, households and businesses is expected to be the most sustainable and significant source of funding for adaptation. Its effectiveness depends on what local and higher-level governments do to encourage and support this, as well as helping deliver infrastructure and services. Hence, a range of innovative fiscal instruments, measures to attract 'climate-smart 'public and private investment and micro-insurance coverage of lower-income households, risk transfer mechanisms and innovative market-based insurance coverage, will be needed to address climate adaptation finance needs. This will need a supportive public policy environment to enable efficient market resource allocation to promote adaptation and overcome persistent market barriers. It also needs frameworks for land-use management to ensure appropriate economic and livelihood development incentives, avoid high-risk zones and implement appropriate building and infrastructure standards. A growing share of current development finance is being committed (in principle) to adaptation, especially towards technological investment and capital projects. However, mechanisms are not yet in place to ensure that it supports locally-driven adaptation practice in urban centres. There is a need to reconcile top-down and bottom-up planning, enabling structured planning, programming and outcome monitoring. A key to improving effectiveness of international public finance will be building the capacity for country-led planning processes that include urban adaptation and are backed by adaptation monitoring and data collection, designed specifically for the complexity of urban projects. The systematic programming of adaptation into international humanitarian and disaster response funding is still to develop. In addition, most national Action Plans under the UNFCCC have little emphasis on urban adaptation. Thus, urban climate adaptation financing and structuring remains an area where innovation and improvement are much needed to deliver demand-driven and responsive solutions, while catering to local contexts and possibilities. [8.4, 8.5]

8.1. Introduction

8.1.1. Key Issues

Successful adaptation to climate change depends centrally on what is done in urban centres – that now house more than half the world's population and concentrate most of its assets and economic activities. As 8.4 emphasizes, this needs to include responses by multiple levels of government, individuals and communities, the private sector and civil society. The serious impactsof extreme weather on many urban centres each year show risks and vulnerabilities that need to be addressed and climate change will usually add to these. What is done in urban centres also has major implications for mitigation, especiallyfuture levels of greenhouse gas emissions and for delivering co-benefits, as discussed in WGIII. This chapter focuses on the connections between urban centres and climate change and on the possibilities for governments, enterprises and populations to adapt to and develop resilience to its direct and indirect impacts.

As discussed in 8.4, most of the investment required for sound adaptation will come from a multitude of small-scale private decisions spanning individuals, households, communities and firms. Furthermore, the level of funding needed for urban adaptation exceeds the capacities of local and national governments and international agencies. This might suggest little role for governments – and especially local governments. But whether or not the 'multitude' of small scale private decisions do contribute to adaptation (and resilience to climate change's impacts) depend on what local governments do, encourage, support and prevent – as well as their contribution to providing needed infrastructure and services. An important part of this is providing an appropriate regulatory framework that supports adaptation (and prevents maladaptation) in the choices made by individuals, households and firms – for instance in the management of land use (with new sites available for development, dangerous sites avoided and key ecological services protected) and the application of building standards within their jurisdiction.

In reviewing adaptation needs and options for urban areas, the documentation points to two key conclusions. The first is how much the adaptive capacity of a city depends on: past plans and investments in infrastructure and services; existing capacities for such investments and land-use management; and for ensuring buildings meet health and safety standards. This provides the foundation for city resilience on which adaptation can be built. For almost all urban centres in low-income and many in middle-income nations; there is little of this foundation of resilience. The second is the importance of city and municipal governments acting now to incorporate climate change adaptation into their development plans and policies. But to do so requires not only building the foundation of resilience (and its institutional and financial underpinnings) but also to mobilize new resources and continuously develop local capacities to respond. This is not to diminish the key roles of other actors including the private sector, the demands and priorities of residents, civil society and higher levels of government. But it will fall to city and municipal government to provide the scaffolding and regulatory framework within which all other stakeholders contribute and collaborate. Thus, adaptation in urban areas depends heavily upon the competence and capacity of local governments and a locally rooted iterative process of learning about changing risks and opportunities, identifying and evaluating options, making decisions, and revising strategies in collaboration with a range of actors (see Chapter 2 for more discussion of this).

8.1.2. Scope of the Chapter

This chapter focuses on what we know about how climate change will impact on urban centres and their populations and enterprises, what measures can be taken to adapt to these changes (and protect vulnerable groups) and the institutional and governance changes needed to underpin this.Both this chapter and Chapter 9 on rural areas highlight the multiple linkages between rural and urban areas. This chapter also has overlaps with Chapter 10, especially in regard to infrastructure, although this chapter focuses on urban infrastructure and in particular the infrastructure that comes within the responsibilities or jurisdiction of urban governments.

This chapter draws its urban statistics from the United Nations Population Division (see United Nations 2012). Urban centres vary from metropolitan areas with more than 20 million inhabitants to those with few thousand (or in some nations a few hundred) inhabitants. There is no international agreement as to how urban centres or populations should be defined or distinguished from rural populations and there is considerable variation in how governments choose to define urban areas (see United Nations 2012). This influences the proportion of the population said to live in urban areas for any nation. Many nations define as urban centres all settlements with populations above a threshold - for instance 1,000 or 2,500 or 5,000 inhabitants. So a nation's urban population and level of urbanization can vary substantially, depending on which threshold is used (or other criteria chosen and applied). Virtually all nations classify settlements with 20,000 plus inhabitants as urban; it is around the proportion of the population that live in settlements between a few hundred and 20,000 inhabitants that national differences emerge. There is also the ambiguity as to the dividing line between rural and urban. In some instances, urban boundaries include large rural areas while in others, urban centres have grown beyond official boundaries and into areas that are within neighbouring jurisdictions and may be defined as rural. Most large cities have more than one boundary – for instance one based on the local government jurisdiction or linked to the built up area, another based on the metropolitan area and another on the metropolitan region or planning region. Boundaries for metropolitan areas or extended metropolitan regions often include substantial rural populations. Most suburban areas are within urban boundaries. In addition, just as urban centres depend on rural resources and eco-system services, it is common for a proportion of the workforce in larger urban centres to live outside the urban centre and commute – and this may include many that live in settlements designated as rural. There is also no agreed definition for what constitutes a city – although the term city implies an urban centre with some economic, political or cultural importance so it would not be applied to most small urban centres.

8.1.3. Context – An Urbanizing World

In 2008, for the first time, more than half the world's population was livingin urban centres and the proportion living in urban centres continues to grow (United Nations 2012). Three quarters of the world'surban population and most

of its largest cities are now in low- and middle-income nations. UN projections suggest that almost all the increase in the world's population up to 2050 will be in urban centres in what are currently low- and middle-income nations (see Table 8-1). It is within urban centres within most nations and globally that most GDP is generated and most new investment has concentrated (World Bank 2008, Satterthwaite et al. 2010).Clearly, in terms only of the population, economic activities and climate risk they concentrate and the progressive increase in such concentration, adapting urban areas to climate change needs serious attention.

[INSERT TABLE 8-1 HERE
Table 8-1:The distribution of the world's urban population by region, 1950–2010 with projections to 2030 and 2050.]

There is an economic logic underpinning most urbanization as all wealthy nations are predominantly urbanized and as rapid urbanization in low- and middle-income nations is usually associated with rapid economic growth (ibid). Most of the world's largest cities are in its largest economies (ibid). If rapid urbanization and rapid city population growth is associated with economic success, it suggests that more resources can be drawn on to support adaptation. But in most urban centres in low- and middle-income nations, including many successful cities, local governments have been unable to keep up with the economic and physical expansion and there are large deficits in provision for infrastructure and services that have relevance for climate change adaptation. Around one in seven of the world's population live in poor quality, overcrowded accommodation in urban areas with inadequate or no provision for basic infrastructure and services and mostly in informal settlements (UN-Habitat 2003, Mitlin and Satterthwaite 2013). Within the world's urban population, it is in these settlements that much of the risk and vulnerability to climate change is concentrated. And a substantial proportion of these settlements are in economically successful cities (Mitlin and Satterthwaite 2013). So this chapter is concerned not only with an adaptation deficit for urban centres but also with a development deficit that has relevance for risk and vulnerability to climate change.

Many aspects of urban change in recent decades have been so rapid that they have overwhelmed government capacity to manage it. Of the world's cities with 750,000 plus inhabitants in 2010, 52 had populations growing more than twenty fold since 1960 and 116 had populations growing more than tenfold (statistics in this paragraph drawn from data in United Nations 2012). The increasing concentration of the world's urban population and its largest cities outside the nations with the highest incomes that Table 8-1 shows represents an important change. Over the 19th and 20th centuries, most of the world's urban population and most of its largest cities were in its most prosperous nations. Urban areas in low- and middle-income nations now have close to two-fifths of the world's total population and close to three-quarters of its urban population. They also have most of the world's large cities. Of the 23 'mega-cities' (cities whose population was reported to exceed 10 million) by 2011, only 5 were in high-income nations (two in Japan, two in USA, one in France). Of the remaining 18, four were in China; three were in India and two in Brazil. However, over three fifths of the world's urban population is in urban centres with less than 1 million inhabitants and it is in these that much of the growth in urban population is occurring.

Underlying these population statistics are large and often complex economic, social, political and demographic changes including the multiplication in the size of the world's economy and the shift in economic activities and employment structures from agriculture to industry and services (and within services to information production and exchange).One of the most significant changes has been the growth in the size and importance of cities whose economies increased and changed as a result of globalization (Sassen 2006). Another is the many large cities that are now centres of large extended metropolitan regions.

One difficulty that this chapter faces is in providing a summary of trends for settlements that have more than half the world's population when there is such diversity among these in terms of their current vulnerability to extreme weather, the scale and nature of risks that climate change is bringing or will bring (and who is most at risk), the extent to which their population lives in good quality homes served with conventional infrastructure and services that provides the basis for adaptation (what this chapter terms accumulated resilience) and the extent to which their governments are acting or able to act on adaptation and being supported to do so by higher levels of government and where needed international agencies. Table 8-2 illustrates this diversity and how each urban centre falls within a spectrum in at least four key factors that influence adaptation: local government capacity, the proportion of the population served with risk-reducing infrastructure and services; the proportion of the population living in housing

built to appropriate health and safety standards; and the levels of risk from climate change's direct and indirect impacts. This chapter also draws on detailed case studies of three cities to illustrate this diversity – New York (Solecki 2012a), Durban (Roberts and O'Donoghue, 2013) and Dar es Salaam (Kiunsi, 2013).

[INSERT TABLE 8-2 HERE
Table 8-2: The large spectrum in the capacity of urban centres to adapt to climate change. One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centres. There are tens of thousands of urban centres worldwide with very large and measureable differences between them in population, area, economic output, human development, ecological footprint and greenhouse gas emissions. The differences in adaptive capacity are far less easy to quantify. This Table seeks to illustrate differences in adaptive capacity and factors that influence it.]

Many attributes of urban centres can be measured and compared. Populations vary from a few thousand inhabitants (or a few hundred in some nations) to the largest cities with 20-36 million inhabitants. Areas vary from less than one to thousands of square kilometres. Average life expectancy at birth for urban centres varies from over 80 years to under 40 years – and under-five mortality rates vary by a factor of 20 or more (Mitlin and Satterthwaite 2013). Average per capita incomes vary by a factor of at least 300; so too do the investment capacities of urban governments (UCLG 2011). Greenhouse gas emissions per person vary by more than 100 (Dodman 2009, Hoornweg et al. 2011). There are large differences between urban centres in the extent to which their economies are dependent on climate-sensitive resources (including commercial agriculture, water and tourism).There are also large variations in the scale and nature of impacts from extreme weather. As Table 8-2 suggests, there are urban indicators that are relevant for accumulated resilience to climate change impacts (the proportion of the population with water piped to their homes, sewers, drains, health care and emergency services) but less so for the scale and nature of climate change related risks and for the quality and capacity of government.

Recent analyses of disaster impacts show that urban centres concentrate a high proportion of theworld's population most affected by extreme weather events (United Nations 2009, 2011, IFRC 2010). As shown in Table 8-2, a high proportion of such urban centres have local governments that lack the capacity to reduce such disaster risk and very large deficits in the infrastructure and institutions needed to do so. Their low-income households may require particular assistance due to greater exposure to hazards, lower adaptive capacity, more limited access to infrastructure or insurance, and fewer possibilities to relocate to safer accommodation as compared to wealthier residents. There are also many cities that have high resilience to extreme weather and have the infrastructure and institutions that can provide resilience to the exacerbation of extreme weather events and change in resource availabilities associated with climate change.

All successful urban centres have had to adapt to environmental conditions and resource availabilities, although local resource constraints have often been overcome by drawing resources and using sinks from 'distant elsewheres' (Rees 1992, McGranahan 2007); this includes importing goods that are resource intensive and whose fabrication involves high greenhouse gas emissions. The growth of urban population over the last century has also caused a very large anthropogenic transformation of terrestrial biomes. Urban centres cover only a small proportion of the world's land surface; Schneider et al 2009 suggested that they cover only 0.51 per cent of the total land area and among the world's regions only in Western Europe did they cover more than 1 per cent. However, their physical and ecological footprints are much larger, as urban based enterprises and consumers draw on a much larger land area. The net ecological impact includes the decline in the share of wild and semi natural areas from about 70 per cent to under 50 per cent of the land area. This was largely to accommodate the demand for crop and pastoral land to support human consumption, leading not only to a decrease in biodiversity but a threat to ecological services that support both rural and urban areas. Future projections (Seto et al 2012) suggest that if current trends continue, that urban land cover will increase by 1.2 million square kilometres by 2030. This would represent nearly tripling the global urban land from around 2000 and would result in a "considerable loss of habitats in key biodiversity hotspots" destroying the green infrastructure that will be key in helping areas adapt to the impacts of climate change (ibid page 16083)

Many of the challenges and opportunities for urban adaptation are derived from the central features of city life – the concentration of people, buildings, economic activities and social and cultural institutions (Romero-Lankao and Dodman 2011). A key part of urban centres' adaptive capacity is related to agglomeration economies. These are

usually discussed in relation to the advantages for enterprises locating there. But the concentrations of people, enterprises and institutions in urban areas also provides potential agglomeration economies in lower unit costs for providing each building with piped water, sewers, drains and a range of services (solid waste collection, schools, health care, emergency services, policing) and bringing together people, communities and institutions to respond collectively (Hardoy et al. 2001). But these need to be acted on and to have local governments capable of acting on them. In most urban centres in low- and middle-income nations, these are not acted upon and the result is very large deficiencies in infrastructure and services. Although urban centres in high-income nations are much better served, there may also be particular challenges – for instance in addressing aging infrastructure and in adapting energy systems, the building stock and infrastructure and services to the altered risk set that climate change's direct and indirect impacts will bring (see Zimmerman and Faris 2010 and Solecki 2012a for discussions of this for New York).

Effective urban governments will also need to work with range of government and civil society institutions at local and supra-local levels and to get support and enabling frameworks from higher levels of government. In addition, as this chapter discusses, the concentration of people and economic activities also presents particular challenges for climate change adaptation – including the management of storm and surface run-off and measures to reduce heat islands. Large cities also concentrate demand and need for ecological services and natural resources (water, food and biomass), energy and electricity and these may rely on supply chains that climate change will disrupt. Thus, the increasing concentration of the world's population in urban centres will bring increased risk concentration ofa range of climate-related hazards for a large and growing proportion of the world's population – while also having the potential to support more effective adaptation.

8.1.4. Vulnerability and Resilience

For each of the direct and indirect impacts of climate change, there are groups of urban dwellers that face higher health and other risks (illness, injury, mortality, damage to or loss of homes and assets). This can be on the basis of age (for instance infants or elderly people's greater susceptibility to particular hazards such as heat waves) or health status (for instance those with particular diseases, injuries or disabilities that make them more susceptible to these impacts). Or it may be because they live in locations that face greater risks – for instance on coasts or by rivers where flood risks have increased or will increase. These are often termed vulnerable groups – although to state the obvious, these are only vulnerable to climate change impacts if the hazard poses a risk. Remove the vulnerable population's exposure to the hazard (e.g. drains preventing flooding) and there is no impact. Infants may face serious health risks when water supplies are contaminated by flooding but rapid and effective treatment for diarrhoea and quickly re-establishing availability of drinking quality water greatly reduces impacts (Bartlett 2008). There are also adaptations by individuals, households, communities, private enterprises or government service providers that may reduce risks or reduce exposure.

Although there are many definitions of vulnerability (see for instance Füssel 2007), these agree that it centres on an inability to avoid harm when exposed to a hazard – including an inability to avoid the hazard, anticipate it (and take measures to avoid it or limit its impact), cope with it and recover from it (bounce back) (see also the report Glossary). So vulnerable groups may be identified on the basis of any of these four factors. Adaptation can also include 'bouncing forward' as resilience is increased and so built to protect against future hazards and uncertainty about such hazards.

The term vulnerability is also applied to sectors that may includefood processing, tourism, water, energy and mobility infrastructure and their cross-linkages e.g. perishable commodities dependent on efficient transport. Much tourismissensitive to climate change as it may damage key tourist assets e.g. coral reefs and beaches or make particular locations less attractive to tourists because of changes in temperatures or increases in extreme weather. Oil price changes will affect travel costs.

Certain types of infrastructure on which urban centres rely are more at risk: e.g. most transport, drainage and electricity transmission systems and many water supply abstraction and treatment works. Infrastructure plans and investments generally include some scope for coping with climate variability but in many locations these will need

to increase reserve margins, back up capacity and other structural adaptation measures. Conventional infrastructure investment decision-making may overlook or fail to value needed redundancy. Cities as complex, inter-connected systems are vulnerable to intersectoral connections – for instance the dependence of water supplies, drainage, traffic management, telecommunications, health care services and some trains on electricity supply and the dependence of emergency services on all-weather roads and functioning bridges (da Silva et al 2012, Solecki 2012a).

8.1.4.1. Differentials in Risk and Vulnerability within Urban Centres

In urban centres where virtually all buildings meet health and safety standards, where land-use planning keeps developments from sites at risk and there is universal provision for infrastructure and basic services, the exposure differentials between high- and low-income groups to climate-related risk is much reduced. Although low-income groups are often termed vulnerable, having a low-income and few assets in many of these cities does not necessarily imply greater vulnerability to climate change. In low- and middle-income countries, typically the larger the deficit in infrastructure and service provision, the larger the differentials in exposure to most climate change impacts by income group. This means a disproportionate climate impact on low-income groups in low- and middle-income nations, who are often made more vulnerable because of poor quality and insecure housing, inadequate infrastructure and lack of provision for health care, emergency services and measures for disaster risk reduction.

Where provision for adequate housing, infrastructure and services is most lacking, the capacity of individuals, households and community organizations to anticipate, cope and recover from the direct and indirect losses and impact of disasters (of which climate-related events are a sub-set) becomes increasingly important (see 8.4).Here, the speed of response and effectiveness of post-disaster response is especially important to those who are more susceptible and have less coping capacity. Their effectiveness depends on understanding the specific vulnerabilities, needs and priorities of different income-groups, age groups and groups that face discrimination, including that faced by women and by particular social or ethnic groups.

Additionally, a growing literature on successful urban adaptation interventions shows that they recognize the interrelations and interdependence between multiple sectors, levels and risks in a dynamic physical, economic, institutional and socio-political environment (Gasper et al., 2011, Kirshen et al., 2008). Therefore, climate policies may need to be embedded in responses to multiple risks and stresses (Reid and Vogel 2006).

8.1.4.2. Understanding Resilience for Urban Centres in Relation to Climate Change

A literature discussing resilience to climate change for urban centres and what contributes to this has emerged in recent years - and this section draws on this literature (Miller 2007, Pelling 2011a, Leichenko 2011, da Silva et al. 2012, Tyler and Moench 2012, Brown et al. 2012). Although resilience is usually considered to be the opposite of vulnerability, vulnerability is often discussed in relation to particular groups within the population whereas resilience is more often discussed in relation to what helps protect them such as infrastructure or climate-risk sensitive land-use management. Addressing resilience for cities is also more than identifying and acting on specific climate change impacts as it looks to the performance of each city's complex and interconnected infrastructure and institutional systems and includes a capacity to withstand unexpected or unpredicted changes. When considered for cities, it is common for certain characteristics of resilience to be identified – for instance flexibility, redundancy, responsiveness, capacity to learn and safe failure (Moench et al., 2012, Tyler et al. 2012, da Silva et al. 2012, Brown et al. 2012). There is also recognition of the complexities of urban systems and the multiple inter-dependencies between different sectors that were noted above.

But when considering a specific city, the level and forms of resilience are often related to specific local factors, services and institutions – for instance for each district in a city, will the storm and surface drains cope with the next storm (a particularly pressing issue for cities that have heavy rainfall in particular seasons).During heat waves, will measures to help those most at risk from high temperatures work and reach all high-risk groups? Here, resilience is not only the ability to recover from the impact (bouncing back) but the ability to avoid or minimize the need to recover (United Nations 2011). Thus, a considerable part of resilience is the functioning of institutions to provide the

above and the knowledge base needed to do so (da Silva et al. 2012).The emerging literature on the resilience of cities to climate change also highlights the need to focus on resource availabilities and sinks beyond the urban boundaries and it may also require coordinated actions by institutions from other jurisdictions or higher levels of government (for instance watershed management upstream of a city to reduce flood risks see Brown et al. 2012, Ramachandraiah 2011). There are also the slow onset impacts that pose particular challenges and that may also be outside the jurisdiction of urban governments – for instance the impact of drought on agriculture that can raise food prices and reduce rural demand for urban services.

Cities in high-income nations and many in middle-income nations have become more resilient to extreme weather (and most other potential catalysts for disasters) through a range of measures that have responded to risks and to the political processes that demanded such responses (Satterthwaite 2011). This resilience has been built over many decades and often required intense political negotiation. The resilience accumulated through this in what was built and in the capacity of institutions provides resilience to some climate change impacts, even though the measures that built resilience were not in response to climate change impacts (see for instance Hardoy and Ruete 2013 on Rosario, Argentina).What strongly influences resilience to extreme weather for urban dwellers is the quality of buildings (homes and workplaces), the effectiveness of land-use planning and regulation to control development in flood-prone and other high risk areas, the quality and coverage for key infrastructure and services, early warning systems for extreme weather and adequate public response measures, whether their incomes are sufficient to invest part in resilience (living in healthy homes, life insurance, insurance for possessions and home, savings, pensions, asset ownership…), what safety nets are available if income is insufficient and the regulatory framework for ensuring the application of the above. Urban governments have importance for most or all of these, although their provision usually depended on changes at national level – for instance in legislation and in financial support (although political change at national level was also in part driven by political pressure from urban dwellers and innovation by city governments). Private companies or non-profit institutions may provide some of the key services and private companies have key roles in provision and often maintenance of infrastructure -but the framework for provision and quality control is provided by local government or local offices or national or provincial government.

A city's accumulated resilience can be assessed by the extent to which it has reduced hazards, reduced risk and reduced exposure, with particular attention to how this serves or protects vulnerable groups and at-risk areas. Also by the measures in place to enhance capacity to cope and adapt. Such an assessment can also consider how well this 'accumulated resilience' will serve climate change adaptation. Of course, there are hazards that city governments cannot reduce (for instance earthquakes) or that need global action (eg reducing greenhouse gas emissions).

Although the components of accumulated resilience were not in response to risks from climate change, the web of institutions and finances that produced and maintain them provide a base for climate change adaptation (and more broadly for resilience). Building and infrastructure standards can be adjusted if needed (there is infrastructure in place that can be adjusted - for instance increasing capacity for storm and surface water drainage systems), existing service provision can be adjusted for new risks or risk levels (measures to reach populations vulnerable to heat stress during heat waves and within heat islands) and city planning and land-use management can be adjusted to any new or heightened risk (keeping building and city expansion away from areas facing new risk levels).This can be supported by changes in private sector investments (over time shifting away from high-risk areas) and changes in insurance premiums and coverage. So the web of institutions and the buildings, infrastructure and services that have developed in response to non-climate change risks provide a foundation for developing resilience to climate change.They provide the basis on which to build adaptive capacity to withstand climate-change related direct and indirect disturbances. They can also go beyond this and "bounce forward" by building climate resilience through a mix of sound development, disaster risk reduction and ecosystem-based adaptation, rather than incremental adaptation interventions..

Whether they will do so depends on whether urban governments take this on – and whether the demands of their inhabitants and these inhabitants' capacity to organize and get change promote this; also whether the institutions and their complex inter-relationships have the capacity to learn. Obviously, the extent to which these provide or can provide resilience in the future also depends on global agreements that slow and stop the increases in risk from GHG emissions and other drivers of climate change.

Many cities that have accumulated resilience may not act on the changes in hazards and risks that climate change is bringing or will bring. So here, the issue is whether the institutions and political pressures that built the accumulated resilience shift now to resilience as a process – responding dynamically and effectively to evolving and changing climate-related risks (and evolving and changing knowledge bases for this).For cities with accumulated resilience, there may be climate change impacts that such accumulated resilience does not serve - for instance potential disruption to resource flows. Or the actions needed for resilience are outside city boundaries.

For urban centres with little accumulated resilience, *resilience as a process* has importance, both to help reduce over time the (often very large) deficiencies in most or all the infrastructure, services and regulatory frameworks that provide resilience in high-income nations and to build resilience to climate change impacts. For around a third of the world's urban population, this has to be done in a context of limited incomes and assets and poor living conditions and little resilience to any stress or shock. Just an increase in prices of food staples or a drop in income (an income earner being ill or injured) or a new cost (medicines needed for a sick family member) can quickly mean inadequate food and thus hunger and reduced capacity to work and to resist infections.

The above also implies a different perspective on how climate change adaptation needs to be supported. It emphasizes how resilience to climate change impacts is intimately tied to the quality of governance (in which local governance has particular importance) and in the government capacity and willingness to listen to, work with, support and serve those who lack resilience. Here too, the idea of resilience as 'bouncing forward' has importance – as shown by the many successful partnerships between local government and grassroots organizations formed by residents of informal settlements that have built or improved homes and neighbourhoods. This would also be part of the shift from resilience to transformation (see Pelling 2011a, Shaw and Theobald, 2011, Manyena et al 2011).

Thus, resilience can be considered in relation to individuals/households, communities and urban centres. In each, it includes the capacity to take action that avoids a climate change impact (live in safe location, have a safe house, have risk reducing infrastructure), to take action before climate impact takes place to reduce its impact (especially relevant for extreme weather events), to cope with the impact and to bounce back (to the previous state) and to 'bounce forward' to a more resilient state that would lay the ground for transformative adaptation.For urban centres, bounce back includes a government capacity to rapidly restore key services and repair infrastructure and 'bounce forward' is building the socio-institutional processes and capacities that enable the accumulation of resilience.

8.1.5. Conclusions from the Fourth Assessment (AR4) and New Issues Raised by this Chapter

AR4's chapter on Industries, Settlements and Human Society noted that these are accustomed to variability in environmental conditions but more at risk if change is more extreme (e.g. beyond what had been experienced in the past), persistent or rapid, especially if not foreseen and where capacities for adaptation are limited.

Except for abrupt extreme events, climate change impacts are not dominant issues for urban centres but their importance is in their interaction with other stressors that may include rapid population growth, political instability, poverty and inequality, ineffective local governments, jurisdictional fragmentation and aging or inadequate infrastructure. Key challenges to getting attention to adaptation include the difficulties of estimating and projecting the magnitudes of climate risk in particular places and sectors with precision and a weak knowledge base on the costs of adaptation.

AR4 described how the interactions between climate change and global urbanization has led to concentrations of urban populations in low-income nations with weak adaptive capacity. It also described the interactions between climate change and a globalized economy that include long supply chains and impacts spreading from directly impacted areas and sectors to other areas and sectors through complex linkages. Many impacts will be unanticipated and total impacts are also poorly estimated by considering only direct impacts. Key global vulnerabilities include interregional trade and migration patterns.AR4's Chapter 7 also described how climate change impacts and most key vulnerabilities are influenced by local contexts including geographic location, the sensitivity to climate of enterprises located there, development pathways and population groups unable to avoid dangerous sites and homes.

Key risks are most often related to climate phenomena that exceed thresholds for adaptation (eg extreme weather or abrupt changes) and limited resources or institutional capacities to reduce risk and cope (development context). Climate change will increase demands on water and energy supplies and often on health care and emergency response systems.

Individual adaptation may not produce systemic adaptation. In addition, adaptation of systems may not benefit all because of differential vulnerability of particular groups and places. Adaptation will require a greater awareness of threats and alternatives beyond historical experience and current access to finance.

Technological innovation for climate adaptation comes largely from industry and services motivated by market signals and these may not be well matched with adaptation needs and residual uncertainties. Many are incremental adjustments to current business activities. Planning guidance and risk management by insurers will have roles in locational choice for industry.

Certain types of infrastructure are more at risk – including most transport, drainage and electricity transmission systems and many water supply abstraction and treatment works. There is a need to increase reserve margins and develop back up capacity. Adaptation of infrastructure and building stock is often dependent on changes in the institutions and governance framework e.g. in planning regulations and building codes. Climate change has become one of many changes to be understood and planned for by local managers and decision makers.

8.1.5.1. Key Uncertainties and Research Priorities

A range of key uncertainties and research priorities emerge from recent literature:

- The limits to understanding and predicting impacts of climate change at a fine grained geographic and sectoral scale
- Inadequate knowledge on the vulnerabilities of urban citizens, enterprises and centres to the direct impacts of climate change, to second and third order impacts and to the interdependence between systems
- Inadequate knowledge on the adaptation potentials for each urban centre (and its government) and their costs and on the limits on what adaptation can achieve (informed by a new literature on loss and damage)
- Serious limitations on geophysical, biological and socio-economic data needed for adaptation including data on nature-society links and local (fine-scale) contexts (see for instance WMO 2008)
- Uncertainties about trends in societal, economic and technological change with or without climate change including the social and political underpinnings of effective adaptation
- Understanding the different impacts and adaptation responses required to rapid and slow onset disasters

8.1.5.2. What has Changed since AR4

There is now a much larger and more diverse literature on current and potential climate change risks for urban populations and centres and the vulnerabilities of different urban centres and their structure and functioning. There has also been a very large expansion in the literature on urban 'adaptation,' and on building resilience at city and regional scales. This includes a large increase in the number of city governments that have published documents on adaptation. There is more engagement with urban adaptation by some professions (including architects, engineers, urban planners and disaster risk reduction specialists). There are also books that focus specifically in climate change and cities with a strong focus on adaptation (see Bicknell et al 2009, Rosenzweig et al 2011a and UN-Habitat 2011a, Cartwright et al 2012). This makes a concise and comprehensive summary more difficult. But this has also produced more clarity in what contributes to resilience in urban centres and systems. Specifically:

- A more detailed understanding of key urban climate processes and improved analytical and down-scaled integrated assessment models at regional and city scale
- A more detailed understanding on the governance of adaptation in urban centres and the adaptation responses being considered or taken (including a large and important grey literature produced by or for city governments and some international agencies) and in many high-income and some middle-income nations, support for this from higher levels of government

- More nuanced understanding of the many ways by which poverty and discrimination exacerbates vulnerability to climate impacts (see also Chapter 13)
- More detailed studies for particular issues of built environment responses to promote adaptation (see for instance the growth in the literature on green and white roofs)
- More case studies of community-based adaptation in its potential contributions and in its limitations
- More consideration of the role of ecosystem services and of green and blue infrastructure in adaptation
- More considerations on the financing, enabling and supporting of adaptation for households and enterprises
- More on learning from innovation in disaster risk reduction
- A greater appreciation of the inter-dependencies between different infrastructure networks and of the need for adaptation both in 'hard' infrastructure and in the 'soft' institutions that plan and manage it.
- More examples of city governments and their networks contributing to national and global discussions of climate change adaptation (and mitigation) including establishing voluntary commitments (see for instance the Durban Adaptation Charter for local governments) and engaging with the Conference of Parties

8.2. Urbanization Processes, Climate Change Risks, and Impacts

8.2.1. Introduction

This section assesses the connections between ongoing urbanization and climate change in relation to patterns and conditions of climate risk, impact, and vulnerability. The focus is on urbanization and its local, regional and global environmental consequences and the processes that maylead to increased risk exposure, constrain people in high-risk livelihoods and residences, and generate vulnerabilities in critical infrastructure. Understanding urbanization and associated risk and vulnerability distributions is critical for an effective response to climate change threats and their impacts (Romero Lankao and Qin, 2011; Bulkeley, 2010;Solnit, 2008; Satterthwaite, et al., 2009; Vale and Campanella, 2005), promotion of sustainable urban habitats and the transition to increased urban resilience. There is a particular interest in the ability of cities to respond to environmental crises, and the resilience and sustainability of cities (Solecki et al., 2011, Solecki, 2012).

The section assesses the direct impacts of climate change on urban populations and urban systems. Together, direct climate impacts and shifts in urbanization change the profile of societal risk and vulnerability. Both can alter transition pathways that lead towards greater resilience and sustainable practices and the basis of how such practices are managed within a community. Understanding and acting on the connections between climate change and urbanization is crucial since changes in one can affect the other. We investigate a range of direct impacts including those on physical and ecological systems, social and economic systems, and coupled human-natural systems. Where relevant and fundamental to the understanding, cascading impacts (where systems are tightly coupled) and secondary (indirect) impacts also are noted.

8.2.2. Urbanization – Conditions, Processes, and Systems within Cities

8.2.2.1. Magnitude and Connections to Climate Change

Section 8.1 emphasizes how much conditions in urban centres vary, how they are influenced by the proportion of the population with incomes too low to allow them to afford food and non-food needs, the extent to which the whole population (and vulnerable groups within this population) are served by the basic infrastructure and network of services that should serve as the main reducers of risk, the extent to which their site is at risk from climate change impacts, and the competence, capacity and accountability of their government (Pelling,2003; Moser and Satterthwaite, 2008; Hardoy and Pandiella, 2009). Variations in these factors have important consequences for the process of climate change, for how climate change contributes to global environmental change, shaping impacts in urban areas, and for how cities might be able to respond (Stone, 2012; Rosenzweig et al., 2011a; Seto and Satterthwaite, 2010; Seto and Shepherd, 2009; US NAS, 2012; Güneralp and Seto, 2008).

Urbanization can be considered in relation to key qualities and parameters (spatial, temporal, and sustainability) to capture the shifting, complex interactions between climate change and urban growth within a global toregional context. Giventhe significant and usually rising levels of urbanization (see 8.1.3), more people will be exposed to impacts of climate change in urban areas, with a growing proportion being exposed in large centres and megacities (de Sherbinin et. al., 2007; Revi, 2007). Additionally, many smaller urban centres in Africa, Latin America and Asia are growing rapidly but are "often institutionally weak and unable to promote effective mitigation and adaptation actions" (Romero Lankao and Dodman, 2011: 14). It is in the urban centres in these regions with less than a million inhabitants where most population growth is expected (United Nations 2012). It is largely these that have limited institutional and financial capacity to address development challenges and incorporate adaptation and mitigation as elements of urban development.

Urbanization alters local environments via a series of physical phenomena that can result in problems such as heat islands and local flooding that can be exacerbated by climate change. It is critical to understand the interplay between the urbanization process, current local environmental change and accelerating climate change. For example, the past long-term trend in surface air temperature in urban centres has been found to be associated with the intensity of urbanization (Kalnay et al 2006; Ren et al., 2007; Fujibe, 2009; Kolokotroni et al., 2010; Chen et al., 2011; Iqbal and Quamar 2011; Fujibe, 2011; Rim, 2009; Santos and Leite 2009; Tayanc et al., 2009; Sajjad et al., 2009; Jung, 2008; He et al., 2007; Stone, 2007). Climate change can influence the dynamics of the microclimate associated with a given city and a city may likewise alter a localized region's climate. Some coupled processes that may be influenced by the interaction of urbanization and climate change include: changing the effect of urbanization (microscale to mesoscale) by strengthening and/or increasing the range of a UHI, altering small scale processes, such as a land-sea breeze effect, katabatic winds, etc.,modifyingsynoptic scale meteorology (e.g. changes in the position of high pressure systems in relation to UHI events), and the spatial extent and magnitude of climate change (on a city) resulting from global radiative forcing from GHGs.

The dense nature of many large cities (including megacities) produces pronounced urban influences on anthropogenic heat emissions and surface roughness. The level of this impact is linked to the level of wealth, energy consumption and micro and regional climate conditions. Anthropogenic heat fluxes for large cities can be very high: up to 50-500 W m^{-2} has been observed in a global analysis (Flanner, 2009; Allen et al., 2011) in London (Iamarino et al., 2011) and Singapore (Quah and Roth, 2012), with values locally reaching 1500 W m^{-2} in Tokyo (Ichinose et al., 1999). Under clear skies and light wind conditions, large cities can be more than 10°C warmer than surrounding rural environments (Oke, 1982). There is strong seasonal, diurnal, and meteorological variability in temperature which influences the level of significance that these urbanization related changes have on a specific city.

In a review of relationships between coastal megacities and environmental change, Grimmond (2011) found increasing evidence that cities can influence weather (e.g. rainfall, lightning) through complex urban land use–weather–climate feedbacks (see also Ohashi and Kida, 2002). Megacity impact on air flows, especially for coastal cities has been modelled, for New York and Tokyo (Holt et al., 2009; Holt and Pullen, 2007; Thompson et al., 2007). Megacities influence both internal city environmental and regional weather and air quality. Megacity-coastal interactions may also impact the hydrological cycle and pollutant removal processes through the development of fog, clouds, and precipitation in and around megacities and coastal areas (Landsberg, 1970; Ohashi and Kida, 2002; Shepherd et al., 2002). Other modelling efforts define building density and design and the scale of urban development are important local determinants of the influence of urbanization on local temperature shifts (Oleson et al., 2012; Trusilova et al., 2008).

The results of climate modelling exercises indicate an 'urban effect' that leads locally to higher temperatures and reduced humidity while additional warming also marginally increases rainfall over large cities. The replacement of vegetation with urban surface outweighs this positive impact to reduce the overall land carbon sink (Grimmond, 2011). With respect to temperature specifically, Jackson et al. (2010 and 2012) confirm that building material properties are influential in creating different urban climate temperature regimes, which have the potential to alter energy demand for climate control systems in buildings. These results suggest that climate impacts of large cities, including the megacities, are open to change should they be redesigned and use of energy-efficient building materials, passive design technologies and appropriate land-use are scaled up. Urbanization and climate change also will lead to other environmental impacts such as increased levels of surface runoff(Hamdi et al., 2011).

8.2.2.2. Spatiality, Physical Planning, and Climate Change

The pattern of urban spatial development is a critical factor in the interactions between urbanization, climate-related risks, and vulnerability. Urban form densities range from concentrated to dispersed, while most planned urban settlements exhibit declining population density outward from the urban core (Seto et al., 2010; Leichenko and Solecki, 2008). In cities with large fringe and unplanned settlements, this pattern can be reversed. In both cases urban growth is experienced through horizontal expansion and sprawl (United Nations2012; Hasse and Lathrop, 2003). Rapid urban population growth in the last decade has been increasingly marked by growth in vertical density (high-rise living, and working) in many nations, especially in Asia. Higher density living can offer opportunities for resource conservation but also challenges for planning and urban management (see 8.3.3.7).

Many large cities have developed into extended metropolitan regions across a wide range of settlement conditions from low, middle and high-income nations (Seto et al., 2010; Leichenko and Solecki, 2005). In such regions, this can force a multiplication of loci for economic activity, industry, educational excellence, and concentrations of poverty. It is often problematic for these multiple centres to interact in planned ways that can benefit from traditional scale economies, creating pressures for geographical, social, administrative and political fragmentation – leading to a transition from a city with a single centre to city metropolitan region with multiple centres and uni-polarity to multi-polarity which is typically observed in most large city development (Laquian, 2011).

Urban expansion has fostered extensive networks of critical infrastructure, which are frequently vulnerable to climate change (Solecki et al., 2011; Rosenzweig et al., 2011a). For instance, New York City's dispersed communications network faces several climate-related risks. Electrical support facilities can be flooded, while cellphone towers can topple due to strong winds or become corroded as sea levels rise (Zimmerman and Faris, 2010). In Alaska, telecommunications towers are already settling due to warming permafrost (Larsen et al.,2008). During the extreme rainfall event in 2005, Mumbai's telecommunications networks ceased to function due to a mix of overload, shut down of the power system and lack diesel supplies for generators (Revi, 2006). Waterallocation for cities that are rapidly growing and in water-scarce regions, like Delhi and Beijing, are increasingly being strained which can generate increased vulnerability to changes in precipitation patterns associated with climate change.

Settlement patterns strongly shape conditions for climate change adaptation and mitigation (Stone et al., 2010; Biesbroek et al., 2009). For instance, within Toronto, per capita greenhouse gas emissions from housing and transport varied from 1.3 to 13 tCO_2 equivalent when comparing a dense inner-city neighbourhood with good access to public transport with a sprawling outer suburb (VandeWeghe et al., 2007, Hoornweg et al.,2011). Cities generate challenges for adaptation by concentrating people and assets in ways that increase climate-related risks and vulnerabilities. By the same token, urban areas create advantages to support resilience through the "economies of scale and proximity that they present for key protective infrastructure and services for risk-reducing governance innovations..." (Satterthwaite, 2009: 560). Higher-density development with adequate transport links can promote social integration and equity, particularly in cities where low-income households live in peripheral settlements (Dulal et al., 2011). Physical planning interventions can be combined with command-and-control measures (e.g. zoning), land use taxes, price mechanisms, and public education campaigns to promote sustainable transport and settlement patterns (Grazi and van den Bergh, 2008).

8.2.2.3. Temporal Dimensions: Rapid Onset, Slow Onset, Production Cycles

For any city or region, it is important to understand the connections between climate risk and vulnerability and the rate of change in aspects of urbanization including populations and households, urban spatial expansion, and redevelopment of existing urbanized areas. Urbanization is associated with changing dimensions of migration and materials flows both into and out of cities and within them (Grimm et al., 2008). The level of increase or in some cases decrease of these conditions, create a dynamic quality in cities. Urban risks are not static and will continue to change in the future. Rapidly changing cities have the challenge of managing this growth via housing and infrastructure development while also attempting to simultaneously understand the relative impact of climate

change. For example in sub-Saharan Africa, the combination of relatively high population growth rates and increasing levels of urbanization (projected to reach 46 percent by 2030) will bring a corresponding rise in exposure to climate change impacts. The conflation of local environmental change resulting from urbanization with climate change shifts make the identification and implementation of effective adaptation strategies more difficult. For example, water shortages are already a chronic concern for many cities in low and middle income nations and this typically worsensas the population and demand continue to grow (Muller, 2007).Overlaying climate change-related reductions in supply or heightened uncertainties facing water managers with this existing instability creates the conditions for greater management and governance crises (Gober, 2010, Milly et al., 2008*)*.

8.2.2.4. Urbanisation and Ecological Sustainability

The urbanization-climate change connection has important implications for ecological sustainability. Urbanization is one of the key drivers of global environmental change and is directly connected to the question of ecological sustainability, and to the ecological underpinning of urban life (Huang, Yeh, and Chang, 2010). An "important aspect of achieving urban sustainability is strengthening our ability to respond to the changing relation between urbanization and climate" (Grimm et al., 2008:758). As cities grow and change, the demand for resources expands and transforms, increasing cities' ecological footprint (Rees, 1992; Wackenagal et al., 2006)and long distance resource linkages to 'distant elsewheres' (Rees 1992). In many cases, city-resource supply connections have become more distant and more at risk of interruption (e.g., Seto et al., 2012; Jenerette and Larsen, 2006).

Climate change can accelerate ecological pressures in cities, as well as interact with existing urban environmental, economic, and political stresses (Leichenko, 2011; Wilbanks and Kates, 2010). For example, New Orleans' geophysical vulnerability is shaped by its low-lying location, accelerating subsidence, rising sea levels, and heightened intensity or frequency of hurricanes due to climate change—a combination of natural phenomena exacerbated by "settlement decisions, canal development, loss of barrier wetlands, extraction of oil and natural gas, and the design, construction, and failure of protective structures and rainfall storage" (Wilbanks and Kates, 2010:726) ; Ernston et al.,2010). Cities in arid regions already struggle with water shortages often in the context of rising demand, but for many such cities, climate change will further reduce water availability because of shifts in precipitation and/or evaporation (Gober, 2010).

8.2.2.5. Regional Differences and Context-Specific Risks

Case studies and regional reviews assessing urban vulnerabilities to climate change have revealed diverse challenges and large differences in levels of adaptive capacity (Rosenzweig et al., 2011a; Hunt and Watkiss, 2011). For instance, discussions in African cities (Castan Broto et al., 2013; Simon, 2010; Kithiia, 2011) have highlighted the lack of capacity and awareness of climate change, as well as often extremely high levels of vulnerability among the continent's large and rapidly growing urban poor populations. Other reviews have considered cities in Latin America (Luque et al., 2013; Hardoy and Romero-Lankao, 2011), North America (Zimmerman and Faris, 2011), Europe (Carter, 2011), and China (Liu and Deng, 2011). Studies have analyzed Asian cities' health risks due to climate change (Kovats and Akhtar, 2008) and other urban vulnerabilities in South and Southeast Asia (Birkmann et al.,2010; Alam and Rabbani, 2009; Revi, 2009).

The global distribution of urban risks is highly context-specific, dynamic, and uneven between and within regions. Absolute exposure to extreme events over the next few decades will be concentrated in large cities and countries with urban populations in low-lying coastal areas, as in many Asian nations (McGranahan, Balk, and Anderson, 2007). Settlements located in river flood plains also are prone to flooding during extreme or persistent precipitation / severe storm conditions. Urban populations' exposure to climate change related risks is influenced by the scale of the population concentration in cities and the proportion of the population in urban areas. However, recent improvements in urban governance and rising wealth in Latin America (one of the world's most urbanized regions) have helped to strengthen adaptive capacity (Hardoy and Romero-Lankao, 2011).

Studies from different cities confirm how much the scale and nature of climate change risks will differ; Section 8.1 and Table 8-2 also emphasized the very large differences between cities in their current resilience to such risks, in the capacity to adapt and in the proportion of their population in informal settlements, most of which lack risk-reducing infrastructure. Many are on dangerous sites including steep slopes and low lands adjacent to unprotected river banks, ocean shorelines and have structures that do not meet building codes (Hardoy et al., 2001; Pelling, 2003). However, those who are generally most vulnerable to climate change impacts are women, children, health compromised and the elderly among this population in informal settlements due to the fact that either they are less mobile (e.g., women with child care responsibilities), have less resources, or are physically weak. Hence, the combination of a lack of infrastructure access, low incomes and limited assets puts them at high risk from disasters (Moser and Satterthwaite, 2008).

8.2.3. Urbanization and Climate Change and Variability – Primary (Direct) and Secondary (Indirect) Impacts

Climate change will lead to increased occurrences and intensity of extreme weather events such as heavy rainfall, warm spells and heat events, drought, intense storm surges and associated sea-level rise (see SREX IPCC 2012; Hunt and Watkiss, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig et al., 2011a). Physical factors such as topography and geo-hydrological conditions typically differentiate variations in the distribution of impacts within an urban area. Social (e.g. equity and justice issues), geographic (e.g. high density locations, suburban, exurban locations) and temporal (e.g. short, medium, and long term shifts) contexts should also be considered.

8.2.3.1. Urban Temperature Variation: Means and Extremes

Heat waves and warm spells will connect with urban heat island effects resulting in increased air pollution (Blake et al., 2011; Campbell-Lendrum and Corvalán, 2007) and may cause heat-related health problems (Hajat et al., 2010; see also 8.2.3.7). Conversely, widespread reduction in cold waves will induce shifts in heating demands (Mideksa and Kallbekken, 2010) and potential reduction in mortality from cold waves. Increased warming is predicted in a wide variety of cities including sub-tropical, semi-arid, and temperate sites with respect to human thermal comfort level (Thorsson et. al., 2011). For more discussion on cities and impacts of increased warming in specific regions refer to the regional chapters of this report. It is still unclear whether or not climate change will exacerbate the UHI phenomenon in cities (Oleson et al., 2012).

8.2.3.2. Urban Heat Islands

Urban heat islands are difficult to quantify and there is debate within the literature on how to define them (Stewart, 2011). Many studies indicate that the UHI will decrease or at least stay constant in the future (Oleson et al., 2012). In London, urban heat islands were observed with recorded night-time temperatures up to 7ºC higher in central London than in Wisley, a rural location 32 km to the southwest (Wilby, 2007). Although small urban centres may also experience the UHI, the extent of urban-rural temperature different are not linearally related to urban population size (Smith and Levermore, 2008). Studies have also linked the extent and expansion of urbanization with past UHI trends, urban heating, current variability, and projected climate change. Recent studies with physically based models such as Oleson (2012) and McCarthy et al. (2010) show mixed signals with reductions in UHI in many areas of the world and increases in some areas in response to climate change simulations. McCarthy et al. (2011) looks specifically at London and Manchester and does not find an increase in UHI in the 2050s.

Future projections of UHI under global warming conditions were conducted for Tokyo. The air temperature of Tokyo in August is projected to increase about 2ºC by the 2070s according to an average of 5 GCMs under the SRES A1b scenario (the range of uncertainty in GCMs is about 2ºC). Another warming of about 0.5ºC is projected due to the maximum possible land-use change. As a result, total UHI intensity is projected to increase from 1.5ºC to 2.0ºC through the 2070s (Adachi et al., 2012).

London's annual number of nights with heat islands stronger than 4ºC has increased by 4 days/decade since the late 1950s; meanwhile, the average nocturnal heat island intensity rose by just ~0.1ºC/decade over the same period (Wilby, 2007). Projections suggest that by 2050, London's nocturnal UHI in August could rise another 0.5°C, representing a 40 percent increase in the number of nights with intense UHI episodes (*ibid*). For New York City, climate change is expected to exacerbate the existing UHI conditions via increase of extended heat waves (Rosenzweig et al., 2009).

For cities in India, connections between urbanization and the development of UHI, and the implications with future climate have been defined (Mohan et al., 2011a; 2011b; 2012). Overall, there is evidence that a current trend of increasingly frequent extreme events will increase with climate change (Manton, 2010). The inter-comparison of the annual mean minimum temperatures of two stations within Delhi (Safdarjung and Palam) post 1970's onwards show that night time temperature trends are synchronized with the city's pace of urban expansion (Mohan et al., 2011b).

8.2.3.3. Drought and Water Scarcity: Means and Extremes

Drought can cause many impacts in urban areas, including increases in food prices and food insecurity because of reduced supply, water shortages, electricity power shortages for urban areas that depend mostly on hydropower and an increase in water related diseases; these may also lead to a wide set of economic impacts as well as increased rural to urban migration (Farley et al., 2011; Herrfahrdt-Pahle, 2010; Vairavamoorthy et al., 2008). Averaging across all climate changescenarios, recent findings suggest that nearly 100 million more city-dwellers "will live under perennial water shortage under climate change conditions than under current climate" (McDonald et al., 2011:2). The study also notes the role of demographic growth: The model results show that currently 150 million people live in cities with perennial water shortage, defined as having less than 100 L per person per day of sustainable surface and groundwater flow within their urban extent" and by 2050, this figure could increase to almost 1 billion (ibid.). Drought and water scarcity also affect cities in high-income countries. A detailed economy-wide, 70-industry analysis of the economic impacts of climate change on water availability in the USA for 2010 through 2050 highlighted the interacting industry-level effects, employment impacts, consequences to personal income, and ramifications for the U.S. Gross Domestic Product (GDP). When compared to a baseline economic forecast, the calculations produced an average risk of damage of $1 trillion to the U.S. economy from climate change over the 40 years, with losses in employment equivalent to nearly 7 million full-time jobs (Backus et al., 2012).

8.2.3.4. Coastal Flooding, Sea Level Rise, and Storm Surge

Sea-level rise represents one of the primary shifts in urban climate change risks, given the increasing concentration of urban populations in coastal locations and within low-elevation zones (McGranahan et al., 2007). Rising sea levels, the associated coastal and riverbank erosion, or flooding in conjunction with storm surge could all lead to widespread impacts on populations, property and coastal vegetation and ecosystems, and threats to commerce, business, and livelihoods (Nicholls 2004, Hanson et al., 2011; Carbognin et al., 2010; Pavri et al., 2010; El Banna and Frihy, 2009; Zanchetting, 2007; Dossou and Glehouenou-Dossou, 2009). It is the lowland areas in coastal cities such as Lagos, Mombasa, or Mumbai that are usually more at risk of flooding, especially if a city also has less provisions for drainage (Adelekan, 2010; Awuor et al., 2008; Revi, 2009). Structures constructed on infilled soils in the lowlands of Lagos, Mumbai and Shanghai are more exposed to risks of flood hazards than similar structures built on consolidated materials (*ibid.*). Many coastal cities have sites at risk from both riverine and coastal storm surge (Mehrotra et al., 2011a).

Cities with extensive port facilities and large scale petro-chemical and energy related industries are vulnerable to climate change's increased flooding potential. Hanson et al. (2011) estimate the change in flooding, by the 2070s in the exposure of large port cities to coastal flooding with scenarios of socio-economic growth, sea level rise and heightened storm surge, and subsidence. They find that population at risk could more than triple while asset exposure is expected to increase more than ten-fold with a 0.5 meter rise in sea-level. The study identifies the "top-20" cities for both population and asset exposure to coastal flooding. The high risk cities in both the current and 2070 rankings are spread across low, middle, and high-income nations, but are concentrated in Asian deltaic cities.

The cities include: Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, New York, Osaka-Kobe, Alexandria, Tokyo, Tianjin, Bangkok, Dhaka, and Hai Phong. Using asset exposure as the metric, cities in high-income nations and in China figure prominently - Miami, New York City, Tokyo and New Orleans as well as Guangzhou, Shanghai and Tianjin. These analyses which highlight the large number of assets and population which will be exposed and vulnerable underscores the need for long-term urban risk reduction measures.

8.2.3.5. Inland Flooding and Hydrological and Geo-Hydrological Hazards at Urban Scale

The exposure to climate related hazards will vary due to differences in the geomorphologic characteristics of the city (Luino and Castaldini, 2010). Heavy rainfall and storms surges would impact urban areas through flooding which in turn could lead to the destruction of properties and public infrastructure, contamination of water sources, water logging, loss of business and livelihood options and increase in water borne and water-related diseases as noted in wide range of studies (Revi, 2007; Dossou and Glehouenou-Dossou, 2007; Kovats and Akhtar, 2008; Sharma and Tomar, 2010; Adelekan, 2010; Hardoy and Pandiella, 2009; de Sherbinin et. al., 2007; Douglas et al., 2008; Roberts, 2008; Nie et al., 2009; Shepherd et al., 2011). Case studies of inland cities have considered the elevated risk of flooding due to climate change, such as in Kampala (Lwasa, 2010; Lwasa, 2013) and travel disruptions in Portland (Chang et al.,2010). Significant research focus has been on attempts to improve modeling of the frequency and condition of extreme precipitation events and resulting flooding (Ranger et al., 2011; Onof and Arnbjerg-Nielsen, 2009; Nelson et al., 2009; Olsson et al., 2009; Sen, 2009).

8.2.3.6. Air Pollution: Means and Extremes

Climate change is associated withimplications for urban air quality (Athassiadou et al., 2010), air pollution, and health policy (see Chapter 11 of WGI AR5 for more discussion). Urban air quality in most cities already is compromised by localized air pollution from industry andtransportation, and often commercial and residential sources. Air quality can be adversely affected by limited ventilation within and aroundstructures. Emerging literature on climate change and air quality shows that there is strong evidence that climate change would generally increase ozone in the US and Europe, but that the pattern of that change is not clear, with some areas increasing and some decreasing. The effects on particulate matter (PM) are also unclear, as are the effects on ozone and PM outside of the US and Europe. Effects on particular urban areas are highly uncertain and may include increases and decreases of certain pollutants (Weaver, 2009; Jacob and Winner, 2009).

8.2.3.7. Emerging Human Health, Disease, and Epidemiology Issues in Cities

Good evidence exists that temperature extremes (heat and cold) affect health, particularly mortality (see 11.2.2). The impacts vary by setting, but populations in urban areas appear more sensitive to heat effects than rural areas in temperate zone countries. Since AR4, there have been more studies on urban populations in low and middle income countries (see for instance Burkart et al 2011 for urban populations in Bangladesh and Egondi et al 2012 for children and non-communicable disease deaths in Nairobi's informal settlements). Heat waves are known to have significant impacts on health that can be exacerbated by drought conditions or high humidity. Studies in high-income countries suggest a greater vulnerability among the elderly to heat-related mortality (see Åström et al 2011 for a review of this). In urban settings where child mortality is high, high and low temperatures have been shown to have an impact on mortality (e.g. Egondi et al. 2012). Furthermore, some occupations are more at risk as they are exposed to higher temperatures for long durations and low-income households are more at risk when heat waves disrupt or limit income-earning opportunities (Kovats and Akhtar 2008) (see also 11.2.7 for more detailed discussion of occupational heat stress).

WHO (2012) notes that climate change may affect the future social and environmental determinants of health, including clean air, safe drinking water, sufficient food and secure shelter. All these are relevant to urban areas. Increased risks from water scarcity, heat waves and flooding were discussed ready. The incidence of asthma exacerbation may be affected by any climate-change related increases in ground level ozone exposures (Barata et al.,

2011; O'Neill and Ebi, 2009; Reid et al., 2009; Gamble, 2009b; Kinney, 2008); other pollutants may also be affected particularly in those cities with PM10 and ozone levels far above WHO guidelines (WHO 2011b). Climate change may affect the distribution, quantity, and quality of pollen in urban areas, as well as altering the timing and duration of pollen seasons. WHO (2012) also noted that diarrhoeal diseases, malnutrition, malaria and dengue are climate-sensitive and in the absence of appropriate adaptation responses, could be adversely affected by climate change (see chapter 11).

8.2.4. Urban Sectors: Exposure and Sensitivity

This section assesses how the observed and forecasted direct impacts of climate change influence the exposure of city residents, infrastructure, and systems to risk by considering key affected sectors and populations and possible interrelations. Direct impacts include all costs and losses attributed to the impact of hazard events, but exclude systemic impacts for example on urban economies through price fluctuations following disaster or the impact of disaster losses on production chains (see UN-ECLAC 1991). Both the temporal and spatial scale of the shifts in climate risk across cities and urbanizing sites in the next few decades are considered. In addition, we analyze how the scale and character of risks change and grow in cities as shifts in climate extremes, means and long-term trends (e.g. sea-level rise) take place.

Climate change will have profound impacts on a broad spectrum of city functions, infrastructure, and services and will interact with and potentially exacerbate many existing stresses. These impacts can occur both *in situ* and through long-distance connections with other cities and with rural locations, such as sites of resource production and extraction (Seto et al., 2012; Satterthwaite et al., 2010). The interaction between climate change and existing environmental stresses can lead to a range of synergies, challenges, and opportunities for adaptation with complex interlinkages and often highly uncertain or non-linear processes (Ernston et al., 2010). For example, the 2007 floods in the city of Villahermosa covered two thirds of Tabasco State in Mexico with serious consequences for the city's economic base. Regional damages and asset and infrastructure losses amounted to US$ 3.1 billion, equivalent to 30 percent of the state annual GDP (CEPAL, 2008). The flood that struck the Chao Phraya River in 2011 not only caused a high loss of life and damages to many companies and several industrial estates in Bangkok but also had a wider economic impact because of the disruption to industrial supply chains (Komori et al 2012).Urban centres serving prosperous agricultural regions are particularly sensitive to climate change if water supply or particular crops may be at risk. In Naivasha, Kenya, drought threatens high-value export oriented horticulture (Simon, 2010). Urban centres that serve as major tourism destinations may suffer when the weather becomes stormy or excessively hot and lead to a loss of revenue.

Similarly, infrastructure will be impacted by systemic and cascading climate risks (Hunt and Watkiss, 2011). Climate stresses, particularly extreme events, will have effects across interconnected urban systems – both within and across multiple sectors (Gasper et al. 2011). The cascading effects of climate change are especially evident in the water, sanitation, energy and transportsectors, due to the often tightly-coupled character of urban infrastructure systems (see Rosenzweig and Solecki 2010 for a discussion of this for New York City). The U.S. National Climate Assessment effort has looked at the impacts of climate change on infrastructure considering the water, land, and energy nexus, as well as on a large number of industries (Skaggs et al., 2011; Wilbanks et al., 2012). These systemic cascades can have both direct and indirect economic impacts (Hallegatte et al., 2011; Ranger et al., 2011) which can extend from the built environment to urban public health (Frumkin et al., 2008; Keim, 2008).

A critical element of climate impacts is that they will affect infrastructure investments that have long operational lives, in some cases up to 100 years or more (Hallegatte and Dumas, 2009). In low and most middle-income cities very large additional investment is needed to address deficits in infrastructure and services since without this, making the short to long-term trade-off to improve resilience is difficult (Dodman and Satterthwaite, 2009). This deficit provides an opportunity for 'climate smart' infrastructure planning that considers the combined needs of pro-poor development and climate change adaptation and mitigation. This is a more difficult task for cities such as New York with dense aging infrastructure, materials that "may not be able to withstand the projectedstrains and stresses from a changing climate" (Zimmerman and Faris, 2010).

Recent assessments have projected the rising population and asset exposure in large port cities (see 8.2.3.4; also Hanson et al.,2011; Munich Re, 2004), alongside case studies in Copenhagen (Hallegatte et al.,2011) and Mumbai (Ranger et al.,2011). By 2070, the exposed assets in cities such as Ningbo (China), Dhaka (Bangladesh) and Kolkata (India) may increase by more than 60-fold (Hanson et al., 2011).

8.2.4.1. Water Supply, Wastewater, and Sanitation

Water and sanitation systems strongly shape household well-being and health, while exerting a wider influence upon urban economic activities, energy demands and the rural-urban water balance(Gober, 2010). Climate change will impact residential water demand and supply and its management (O'Hara and Georgakakos, 2008).Among the projected impacts of climate change on water are: altered precipitation and runoff patterns in cities, sea level rise and resulting saline ingress, constraints in water availability and quality, and heightened uncertainty in the assumptions that underpin long-term planning and investment in water and waste water systems (Muller, 2007; Fane and Turner, 2010; Major et al., 2011).Local government departments and water utilities responsible for water supply and waste water management must confront these new climatic patterns and major uncertainties in availabilities and learn to respond to a dynamics and evolving sets of constraints (Milly et al.,2008).

Climate change will increase the risk and vulnerability of urban populations to groundwater and aquifer quality reduction (e.g. Praskievicz and Chang, 2009; Taylor and Stefan, 2009) and subsidence and increased salinity intrusion. High levels of groundwater extraction have led to serious problems of subsidence in cities such as Bangkok (Babel et al 2006) and Mexico City (Romero-Lankao 2010) that damages buildings and fractures pipes and can increase flood risks (see also Jha et al., 2012). This problem can be compounded in coastal cities when saline intrusion reduces ground water quality and erodes structures.

In many rapidlydeveloping cities, climate change's impacts on water supplies will interact with growing population, growing demand and economic pressures. This will potentially heighten water stress and increase negative impacts on the natural resource base with impacts on water quality and quantity. Caribbean nations are urbanising with an expanding middle class. This is sharply raising the demand for water and increasing the associated challenges of managing runoff, storm water, and solid wastes (Cashmanet al., 2010). Aggravating such water stresses, climate change could significantly reduce rainfall levels especially during the Caribbean's crucial rainy season (*ibid.*).

In Shanghai, climate change is expected to bring decreased water availability, as well as flooding, groundwater salinization and coastal subsidence. The city's population of 17 million is projected to continue expanding, often within areas that are "likely increasingly flood-prone" (de Sherbinin et al. 2007: 60). Groundwater depletion has contributed to land subsidence in these already vulnerable areas, reinforcing the water stresses and risks of erosion, but Shanghai's wealth and correspondingly greater adaptive capacity may help to manage these complex risks *(ibid.)*. In several large Andean cities, declining volumes of glacial melt water and expected further declines have been observed for several cities (Chevallier et al. 2011; Buytaert et al. 2010).

Several studies estimate how climate change will alter the relationship among water users and the implied tensions over the supply and the demand for water (Tidwell et al., 2011; Roy et al., 2012). Large-scale critical infrastructure such as sanitation systems for cities (e.g. Cape Town – Ziervogel et al., 2010) may also be affected. In small and mid-sized African cities, threats from floods on drinking water quality taken fromwells, is a growing concern (Cisse et al., 2010).

Water shortages will exacerbate existing tensions and conflicts between the various end-uses (residential, commercial, industrial, agricultural, and infrastructural) (Tidwell et al., 2011; Roy et al., 2012).Floods, droughts and heavy rainfall have also impacted agriculture and urban food sources, and climate change can exacerbate food and water scarcity in urban areas (Gasper et al., 2011). Some water systems, under some scenarios and short-term time frames, are not projected to experience negative impacts. For instance, Chicago's Metropolitan Water Reclamation District (MWRD) found that reduced precipitation due to climate change would decrease pumping and general operations costs, since sewers will contain less rainwater in drier seasons (Hayhoe et al.,2010).

Wastewater and sanitation systems will be increasingly overburdened during extreme precipitation events if attention is not paid to maintenance, the limited capacity of drainage systems in old cities, or the lack of any provision for drainage in most unplanned settlements and in many urban centres (Howard et al., 2010; Wong and Brown, 2009, Mitlin and Satterthwaite 2013). In the city of La Ceiba in Honduras, stakeholders concluded that addressing urban drainage and improved management of the Rio Cangrejal watershed were top priority for protecting the population against projected climate change impacts; the city lacks a stormwater drainage system but experiences regular flooding from heavy rainfall and storm surges (Smith et al., 2011). Flooding is often made worse by uncontrolled city development that cause natural drainage channels and flood plains to be built over and a failure to maintain drainage channels (and their blockage by solid wastes where there is no waste collection service). These problems are most evident in urban centres in low- and middle-income nations and where there are no drains or sewers that can help cope with heavy precipitation (see Douglas et al 2008) and no service to collect solid wastes (many cities in low-income nations have less than half their population with a regular solid waste collections service – see Hoornweg and Bhada-Tata 2012). Many cities in high-income nations also face challenges. An analysis of three cities in Washington State sought to assess future streamflows and the magnitudes of peak discharges, concluding that "concern over present (drainage) design standards is warranted" (Rosenberg et al., 2010: 347). Climate change was identified as one of the key drivers affecting Britain's future sewer systems (Tait et al., 2008). According to a model of urbanisation and climate change impacts in an urban catchment, the volume of sewage released to the environment by combined sewage overflow spills and flooding was projected to increase by 40% (ibid).

8.2.4.2. Energy Supply

Since energy exerts a major influence on economic development, health, and quality of life, any disruption or unreliability in power or fuel supplies due to climate change can have far-reaching consequences. Most urban businesses (from the largest to many home-based enterprises), infrastructure, services (including healthcare and emergency services) and residents rely heavily on power supplies (Findland Safety Investigations Authority, 2011; Halsnaes and Garg, 2011; Hammer et al., 2011). This is also true for water treatment and supply, rail-based public transport, road traffic management and often flood-protection measures (Jollands et al.,2007). Power interruptions in communication networks can pose problems for rescue and emergency services that rely on telecommunications for their operations (Safety Investigations Authority of Finland, 2011).

Past experiences with power outages indicate some of the knock-on effects (Chang et al., 2007). New York City's blackout of 2003 lasted 28 hours and halted electricity, mass transport, surface vehicles due to signalling outages, "and water supply for a much longer period" (Rosenzweig and Solecki, 2010). Low-income households in Chittagong utilize candles or kerosene lamps during the city's frequent power outages, which were found to disturb children's studies, increase expenses, and overheat homes (Rahman et al., 2010). A review of climate change impacts on the electricity sector (Mideksa and Kallbekken, 2010) projects reductions in the efficiency of cooling for thermal power, changes in hydropower and wind power potential, and changing demand for heating or cooling in the US and Europe.

Less is known regarding the demand side energy impacts of climate change outside high-income nations. In most urban centres in low-income and some middle-income nations, a significant proportion of the population does not have access to electricity, and energy use in low-income households is still dominated by charcoal, firewood, or biomass based fuels (Satterthwaite and Sverdlik, 2012). Most of these nations are also expected to experience large increases in mean temperatures or rising frequency of heat-waves due to climate change (IPCC 4AR).

Climate change will alter the patterns of urban energy consumption, particularly with respect to electricity demand and/or energy needed for cooling or heating (for a review see Mideksa and Kallbekken, 2010). In settings with extensive air conditioning use, climate change will bring increases in air conditioning demand and in turn heightened electricity demand (Radhi,2009; see also Hayhoe et al.,2010 for a discussion of this in relation to Chicago). In temperate and more northern regions, winter temperature increases will bring decreases in energy demand for heating (Mideksa and Kallbekken, 2010). In most cases within individual cities, potential increases in

summertime electricity demand from climate change will exceed reductions in winter energy demand reductions (Hammer et al., 2011).

Many cities' economies will be impacted if climate change induces water scarcity and variability that interrupt hydropower supplies. If climate changereduces Brazil's hydroelectric generation, this will have negative impacts on the economies of the many urban centres supplied in Brazil as well as across national to neighboring counties(Lucena et al., 2009; Lucena 2010; Schaeffer et al., 2009). Cities in sub-Saharan Africa often rely on hydropower for their electricity, and failures in hydropower supplies "can lead to a more general 'urban failure' " (Muller, 2007). Discussing supply side concerns, Laube et al. (2006) identify water shortages in Ghana following low precipitation periods and competition with hydropower between energy and water provision including to downstream urban centres as a possible impact. Declining water levels in the Hoover Dam have raised the possibility that Los Angeles will lose "a major power source as hydroelectric turbines shut down," and that Las Vegas will experience a severe decline in drinking water availability (Gober, 2010).

Summer heat waves are associated with spikes in demand with extensive use of air conditioning,resulting in brownouts or blackouts (Mideksa and Kallbekken, 2010; Mirasgedis et al., 2007).Cities in the temperate regions of Australia are already experiencing regular blackouts on hot summer days, largely due to increased residential air-conditioner use (Maller and Strengers, 2011). Research in Boston (Kirshen et al., 2008) suggested that rising energy demands in Boston's hotter summers have a "disproportional impact on (the) elderly and poor,increased energy expenditures; loss of productivity and quality of life" (*ibid:*241). Any increase in the frequency or intensity of storms may disrupt electricity distribution systems because of the collapse of power lines and other infrastructure (see for instance Rosenzweig et al., 2011a; 2011b; 2011c; see also Chapter 10).

8.2.4.3. Transportation and Telecommunications

Climate change related extreme events will affect transportation and telecommunication infrastructure including a variety of capital stock in urban areas such as bridges, roads, railways, pipelines, and port facilities, data sensors, and wire and wireless networks (Major et al., 2011; Jacob et al., 2011; Hallegatte et al., 2011; Koetse and Rietveld, 2009). Assessing possible disruptions of transport networks within cities and urban systems is critical. Loss of telecommunication access during extreme weather events can inhibit disaster response and recovery efforts because of its critical role in providing logistical support for such activity (Jacob et al., 2011).

The literature on transport and climate change focuses more on mitigation, with limited attention within the urban literature to adaptation (Hunt and Watkiss, 2011). Existing studies on climate change impacts are often limited to the short term demand side, particularly in passenger transport (Koetse and Rietveld, 2009). However climate change creates several challenges for transport systems. The daily functioning of most transport systems is already sensitive to weather fluctuations including extreme precipitation, temperature, winds, visibility, and for coastal cities, rising sea levels with the associated risks of flooding and damages (Mehrotra et al., 2011b; Love et al., 2010). Transport is thus highly vulnerable to climate variability and change, and the economic importance of transport systems has increased with the rise of just-in-time delivery methods, heightening the risk of losses due to extreme weather (Gasper et al., 2010). In addition to adapting road transport, it will be necessary to ensure bridges, railway cuttings, and other hard infrastructure are resilient to climate change over their service lifespan (Jaroszweski et al., 2010). For railways, few studies have examined the effects of climate change but weatherrelated rail system failures may be caused by high temperatures, icing, and storms (Koetse and Rietveld, 2009; see also Dobney et al 2010 for future heat related delays in UK railways). Very few studies have examined the vulnerability of air and seaborne transport and infrastructure. The impacts of climate change could translate into a greater number and longevity of weather-related delays with extreme weather possibly occurring more frequently and more severely. This would bring further disruptions for aviation (Eurocontrol, 2008) and maritime transport (Becker et al., 2012).

Most cities in low and middle-income nations are still developing their transport systems (Dimitriou and Gakenheimer, 2011), especially in their largerand more rapidly growing cities.For example, Asian cities and the transportation networks located within and around them are often at risk from extreme weather events (Regmi and Hanaoka, 2011). India's transportation and telecommunications networks are still being built, and adaptation as well

as mitigation measures "will need to be integrated within the design of these systems" (Revi, 2009: 329) to maximise co-benefits and synergies and minimise trade-offs (Biesbroek et al., 2009; Hamin and Gurran, 2008).

Loss of sea ice can benefit some cities as it increases opportunities for developing road networks or ports, although it may be costly to adapt the road, air and water transport networks in addition to the known environmental risks associated with such redevelopment (Larsen et al., 2008). For industries and communities in Northern Canada, reduced freshwater-ice levels creates economic benefits such as longer shipping seasons (Prowse et al.,2009). Lost sea ice could also promote new seaports in marine environments, but inland towns require sizable investments in land-based roads to replace winter ice roads that formerly utilised small lakes and stream networks (ibid.). Thawing of permafrost can result in instability and major damage to roads, infrastructure, and buildings in and around northern cities and towns (ibid.).

The direct impacts of extreme weather on transportare often more easily assessed than the indirect impacts or possible knock-on effects between systems. Studies have often examined the direct impacts of flooding upon transport infrastructure, but the indirect costs of delays, detours, and trip cancellation "may also be substantial" (Koetse and Rietveld, 2009). During Mumbai's 2005 floods, there were serious direct impacts in terms of injuries, deaths and property damage but also serious indirect impacts as most city services were shut down for 5 days without contact via rail, road or air (Revi, 2005). Transport and other urban infrastructure networks are often interdependent and located in close physical proximity to one another (Kirshen et al., 2008). Yet only a few assessments have jointly considered the impacts upon transport and other associated sectors (Hayhoe et al.,2010 for Chicago, Kirshen et al.,2008 for Boston).Implementing adaptation strategies in the transport sector requires "coordination at national, regional, and local levels", since climate change impacts are widespread and extend across scales (Regmi and Hanaoka, 2011).

Transportation systems are critical for effective disasters response – for example, where there is an urgent need for evacuating populations prior to an approaching storm or where disaster response requires an urgent need to ensure provision for food, water and emergency services to affected populations.

8.2.4.4. Built Environment, and Recreation and Heritage Sites

Good quality housing should provide its occupants with a comfortable, healthy and secure living environment and protect them from injuries, losses and damage (Haines et al. 2013). For many low-income households, home-based enterprises are also important components of livelihoods. As such, housing has a key role in protecting urban populations and their assets – and has particular importance for protecting vulnerable groups including infants and young children (Bartlett 2008), older residents or those with disabilities or chronic health conditions. This also means protection against displacement since low-income urban dwellers are particularly at risk from disruptions to household income.

Urban housing is "often the major part of the infrastructure affected (by disasters)..." (Jacobs and Williams, 2011:176). Extreme events like cyclones and floods inflict a heavy toll on housing, particularly those structures built with informal building materials and built outside of safety standards (United Nations, 2011). Dhaka's 1998 floods damaged 30% of the city's units and of these, 32% were permanent/semi-permanent homes belonging to wealthier households, but 36% were lower-quality owned by the lower-middle classes and 32% by the poorest (Alam and Rabbani, 2007). Adelekan (2012) shows how a relatively modest increase in wind speeds during storms caused widespread damage and high costs of rebuilding or repairs in central Ibadan. In addition, increased climate variability, warmer temperatures, precipitation shifts, and increased humidity will accelerate the deterioration and weathering of many stone and metal structures in cities (Stewart et al., 2011; Bonazza et al., 2009; Smith et al., 2008; Thornbush and Viles, 2007; Grossi et al., 2007).

Recreational sites such as parks and playgrounds will also be affected. In New York City, recreational sites are defined as critical infrastructure and often located in low elevation areas subject to storm surge flooding (Rosenzweig and Solecki, 2010). Although climate change may have significant impacts on traditional tourist destinations, little research has examined the effects upon urban tourism in particular (Gasper et al., 2011).

The increased risks that climate change is bringing to the built environment (Wilby, 2007;Spennemann and Look, 1998) also means risks to the built heritage. This has led to the Venice Declaration on Building Resilience at the Local Level Towards Protected Cultural Heritage and Climate Change Adaptation Strategies which brings together UNESCO, UN-HABITAT, EC and individual city mayors. One example of this is Saint-Louis in Senegal, a coastal city that is also on the mouth of the Senegal river that has frequent floods and large areas at risk from river and coastal flooding. It is a World Heritage Site and there are initiatives to reduce flooding risks and to relocate families from locations most at risk but the local authority has very limited investment capacity (Diagne 2007, Silver et al., 2013).

8.2.4.5. Green Infrastructure and Ecosystem-based Adaptation

A wide variety of ecosystem services and green infrastructure will be impacted by climate change. Climate change will alter ecosystem functions such as temperature and precipitation regimes, evaporation, humidity, soil moisture levels, vegetation growth rates (and allergen levels), water tables and aquifer levels, and air quality. These can influence the effectiveness of pervious surfaces used in storm water management, green/white/blue roofs, coastal marshes utilized for flood protection, food and urban agriculture and overall biomass production. Mombasa will experience more variable rainfall as a result of climate change, making initiating and expanding green infrastructure more difficult (Kithiia and Lyth, 2011). Trees in British cities will be increasingly prone to heat stress and to attacks by pests, including non-native pathogens and pests that could survive for the first time under warmer or wetter conditions (Tubby and Webber, 2010). Urban coastal wetlands will be inundated with sea level rise. In New York City, remnant coastal wetlands will be lost to sea-level rise because the wetlands will not be able to migrate inland due to bulk heading and intensive coastal development (Rosenzweig et al., 2012).

8.2.4.6. Health and Social Services

The effects of climate change will also be evident across several urban social and public services such as health and social care provision, education, police and emergency services including firefighting and ambulances (see Health, Chapter 11 in this volume for more discussion). Many low and middle-income cities lack adequate social and public service provision (Bartlett, 2008; Satterthwaite et al,2007) while higher-income cities are only beginning to consider climate change in their health or disaster management plans (Brody et al.,2010).Although there are few studies on adapting education, police, or other key services, a growing public health literature has discussed multi-sectoral adaptation strategies (Huang et al., 2011). Cities' existing public health measures provide a foundation for adapting to climate change, such as heat warning systems or disease surveillance (Bedsworth, 2009; McMichael et al., 2008). Negative climate impacts on some of the most vulnerable in society– the very young and children (Sheffield and Landrigan, 2011; Watt and Chamberlain, 2011; Ebi and Paulson, 2010) the elderly (Oven, 2012; White-Newsome et al., 2011) and the severely disadvantaged (Kenny et al., 2010; Ramin and Svoboda, 2009) have been highlighted (see Chapter 11)

8.2.5. Urban Transition to Resilience and Sustainability

The question of how to promote increased resilience and enhanced sustainability in urban areas (as illustrated in Table 8-2) has become a central research topic and policy consideration. What information is needed and what steps should be taken to promote this type of transition are central to this discussion. It is well recognized that climate change risks affect this process byheightening uncertainties and altering longstanding patterns of environmental risks in cities, many of which continue to face other significant stressors such as rapid population growth, increased pollution, resource demands, and concentrated poverty (Mehrotra et al., 2011a; Wilbanks and Kates, 2010). This section discusses how climate change increasingly affects municipal decision-making frames and alters local conceptions of cities as vehicles for economic growth, for political change, for meeting livelihoods and basic needs as well as larger-scale goals of resilience and sustainability.

8.2.5.1. Uncertainty and Surprise

Climate change will contribute to more uncertain and dynamic urban conditions, making past environmental responses and baselines less valuable for predicting cities' future environments (Solecki et al., 2010). It has been suggested that "the complexities and uncertainties associated with climate change pose by far the greatest challenges that planners have ever been asked to handle" (Susskind, 2010:219). Municipal and higher-level adaptation plans will need to take into account uncertainty about future climates and extremes. These will need to consider direct and indirect economic costs, including the trade-off of inaction and locking into ill-adapted infrastructure versus investment in adaptation when climate change is less than anticipated (Hallegatte et al., 2007). Several U.S. studies have considered the cost on inaction for specific states (Wilbanks et al., 2012, Niemi et al., 2009a, 2009b, 2009c, Repetto 2011a, 2011b, 2012a, 2012b, 2012c, 2012d, Backus et al., 2012). An obvious transitional management issue is related to the many urban wastes´ repositoriesaround current city boundaries.

Several decision-making settings in urban areas are influenced by shifts in the likelihood of extreme weather events and the need to respond to climate-related surprises. Water resource managers (Fane and Turner, 2010; Dessai and Hulme, 2007), insurance companies (Crichton, 2007; Botzen et al., 2010), public health, disaster, and emergency responders (Keim, 2008; Huang et al.,2011; Hess et al.,2009) will need to grapple with heightened climate-related uncertainties and the demands of climate proofing. Infrastructure planners need to adopt various strategies to incorporate uncertainty, such as selecting no-regret strategies, favoring reversible and flexible options, buying 'safety margins' in new investments, promoting soft adaptation strategies, and/or reducing decision time horizons (Hallegatte and Dumas, 2009). Other strategies include scenario planning, sensitivity analyses, and examining risk tolerances. New challenges also will arise. For example, the need to expand the agriculture frontier, for increasing food production, will bring agricultural activities closer to the urban boundaries. This means that the fumigation effects will add a new health hazard to urban inhabitants as well as adversely affect water supply.

8.2.5.2. Extreme Event Probability

Shifts in extreme weather and climate event probability have affected how cities are understood by stakeholders and decision-makers - cities are seen as potentially more prone to experience environmental hazards and disasters. It is important to assess how these changes are integrated back into local decision-making. In New York City, the prospect of increased climate variability has spurred an integration of climate resiliency efforts into extreme event planning and actions including increased storm water management during intense precipitation events to forestall or prevent inland and street-level flooding (Rosenzweig and Solecki, 2010). ConverselyJakarta has several early-warning disaster systems in place but no adaptation plans have been developed; Jakarta's Spatial Plan does not incorporate climate change and the local government's focus is on disaster management rather than preparing for climate change (Firmana et al., 2011).

Urban decision-makers have widely divergent motivations and strategies for incorporating extreme events into local adaptation plans. Cities have implemented adaptation measures in response to "specific local or regional natural disasters, which may or may not be climate-related", such as enhancing preparedness measures in the Greater Mumbai Disaster Management Plan after the City's 2005 floods (Revi, 2006; Bulkeley 2010,). Findings in the UK (Tompkins et al.,2010) and other European cities (Carter, 2011) suggest that the primary motives for adaptation measures are rarely climate-related; policymakers instead prioritise biodiversity conservation, energy reduction, or responding to current climate extremes. However, some authors argue that adaptation strategies can be more meaningfully implemented when coupled and integrated within other agendas, such as improving health or enhancing urban competitiveness (Nath and Behera, 2011; Carter, 2011). Further research is needed to evaluate the merits of stand-alone adaptation plans, as opposed to approaches that seek to mainstream climate change into urban planning (Romero-Lankao and Dodman, 2011).

8.2.5.3. Transitions

In recent years, different models of urban environmental transition (e.g. shifts from a sanitary city to sustainable city presented by McGranahan 2007) have been introduced to illustrate how the connections between health hazards and environmental impacts as cities and neighbourhoods develop. This includes the use of global and local sinks for wastes that are outside their boundaries (ibid, Wilson, 2012). Within these models, key variables have been identified that make cities vulnerable to climate change (e.g. extensive infrastructure networks, high density population in exposed or other sensitive sites). Established sustainability approaches e.g. compact cities, eco-regions, polycentric new-town planning systems, urban agriculture, development as a strategy for moderating urbanization (Williams et al., 2012) are among the most common transition strategies. These strategies often are associated with high, often limiting, redevelopment costs.

Climate change has encouraged stakeholders and decision-makers to re-evaluate the environment of their cities as dynamic and connected to several transition contexts, especially with respect to movement toward low-carbon economies (Buckeley et al., 2010; Mdluli and Vogel, 2010). Other transition contexts are associated with an understanding of the urban systems and functions that are increasingly under stress so that past approaches are no longer adequate (Pelling and Dill, 2010).

Transitions in the contextof climate change emerge in two situations. The first is a systems-level perspective where urban systems could reach a tipping point in which a failure or collapse could occur. The second is a broader scale societal transition to enhanced resilience and adaptive capacity (and attention to mitigation) in the face of accelerated climate change (Solecki and Murphy, 2013; Ernstson et al., 2010; Mdluli and Vogel, 2010; Tompkins et al., 2010; Gusdorf et al., 2008; Pelling, 2011a). The latter can often occur without resulting in a broader scale transition (Pelling and Navarrete, 2011) with incremental changes also potentially precipitating regime level shifts. Although such shifts can also happen as a result of discrete regime failure (Pelling, 2011a) this is less common. Such transformational changes have been observed in a variety of urban disaster contexts. Most often they follow urban earthquake events (e.g. in Nicaragua, Guatemala, Turkey) but are also associated with flooding in Bangladesh (Pelling, 2011a). Disasters can enable regime level change at moments in history where competing approaches to development have political voice, an organizational base that articulates competing analysis of the causes of the disaster and weak systemic counter response.

8.2.5.4. Social Dynamics, Economic Tensions, and Multiple Stressors

Climate change may exacerbate existing social and economic stressors in cities with the potential to affect urban livelihoods, engender political or social upheaval, or generate other negative impacts upon humansecurity(Siddiqi, 2011; Simon and Leck, 2010; Bunce et al., 2010 – see regional chapters for this report for more details). Climate change could potentially contribute to violent conflicts and spur migration (de Sherbinin et al, 2011;Adamo, 2010; Reuveny, 2007), yet there is considerable uncertainty regarding projections. Migration may represent an important household strategy to adapt by diversifying income-sources and livelihoods (Tacoli, 2009). Although climate change could significantly disrupt livelihoods, outcomes will depend upon particular social structures, state institutions, and other broader determinants of human security (Barnett and Adger, 2007). In sum, “dwindling resources in an uncertain political, economic and social context are capable of generating conflict and instability, and the causal mechanisms are often indirect” between climate and conflict (Beniston, 2010:567).

Specific tensions emerging from climate change impacts have been derived from studies connecting climate impacts with disaster recovery (Solecki et al., 2011). These tensions include temporary or permanent poverty; food insecurity; lack of access to freshwater; and shifts in the informal economy. Shifts in social dynamics include the possibility and aspiration that reconstruction and recovery can improve people’s livelihoods, changing the structure of the urban economy through the disaster cycle; changes in city administration; private and public property ownership; lifestyle (Coombes and Jones, 2010) and in more dramatic cases change in the urban centre’s economic base. To help understand climate-related tensions in cities, a stronger research focus upon cities, human security, and climate change has been advocated (Simon and Leck, 2010). The links between humanitarian work and climate change are increasingly recognized, but further collaborations between climate scientists, researchers, aid workers,

and international funding agencies is needed (Braman et al., 2010). Holistic strategies help to link development goals with adaptation, so that "multi-dimensional and multi-scale approaches (can) better guide the construction of adaptation responses to climate change and integrate them to development strategies" (Sánchez-Rodriguez, 2009).

Climate change also creates implications for equity from different management solutions (Pelling et al, 2012). For example, the privatization of urban water supply and sanitation systems advantages specific groups over others. Conversely, community-based solutions that also build social capital can be a component in generating generic urban resilience. However, these may exacerbate inequality at the city level with those local areas with strong levels of social capital being able to benefit most from local community led action or support for local initiatives from international and national partners (UN Habitat 2007; Pelling et al, 2012).

8.2.5.5. Historical Analogues

The experience of cities in coping with environmental/resource crises in the past provides a useful analog to understand climate change impacts and shifts in urbanization process (Solecki, 2012; Ranger et al., 2011; Ford et al., 2010; McLeman and Hunter, 2010; Hallegate et al., 2007; Gibbons et al., 2006). Cities often have been able to respond to localized risks and vulnerabilities such as resource shortages and environmental quality issues by externalizing the problems either through expansion of the resource catchment or by externalising the environmental quality threats (e.g. sewerage, rubbish) to more remote and distant locations (McGranahan, 2007; Tarr, 1997). This is more complex in the case of climate change in that the source of the risk and vulnerability is external to individual cities and outside their span of control. City governments have dealt with many environmental health problems by reducing or removing the hazard, but this is beyond their capacities to accomplish with respect to climate change.

Urban development and urbanization has been dramatically impacted by past changes associated with large scale exogenous factors which have either been pervasive (e.g. globalization) and/or profound e.g. wartime devastation, civil war and natural hazards such as earthquakes, cyclones, as well as the application of new technologies (e.g., automobiles, electricity, the internet). Identity is particularly important in this context because the physical fabric can be rebuilt, but in so-doing the identity of a city may be changed. In these situations,, it is evident that well-governed cities demonstrate a capacity to adapt and to learn from crises (Solecki, 2012). As described in 8.3, there is increasing evidence of policy, practice and scientific interest in urban adaptation as a core strategy to address climate change risks.

8.3. Adapting Urban Areas

8.3.1. Introduction

The literature on urban climate change adaptation has increased very significantly since the Fourth Assessment (AR 4). The growing interest in urban adaptation is mainly evident in three aspects. The first is a literature examining risks and vulnerabilities for particular cities. The second, overlapping with this, are papers discussing what might constitute resilience. The third is documentation produced by or for particular city governments on adaptation. There is less documentation of local government decisions to include climate change adaptation in plans and investment programmes, although some city governments report on this (see Solecki 2012, Roberts 2008a and 2010).

Planning urban climate change adaptation faces uncertainties about the magnitude and location of present and future hazard risk and vulnerability at the urban scale as most climate models function at a lower resolution than most cities. The availability of relevant risk data continues to be challenging as it is often not collected. Or if it is, it is rarely quantitative or at the appropriate scale and often fragmented across city departments (Hardoy and Pandiella 2009). Many suggested adaptation measures are in response to specific local or regional hazard risks, which may not be directly climate-related (Bulkeley 2010). Climate data needs to be integrated geographically, across time-scales, and consider the range of regional benefits and costs of climate policy if it is to be useful to and spark local dialogue in adaptation (Ruth 2010).

There is a growing body of literature on opportunities to strengthen urban climate resilience in household, community and city development plans, infrastructure development investment and the management of ecosystems and of cities' physical expansion. City governments that have developed adaptation policies recognize that their strategies, investments and actions plans have to be part of an iterative process that can change with the availability of new information, analyses or frameworks - as presented in the "Iterative Risk Management Approach to Climate Change" (National Research Council 2011). What is important is the recognition by local governments of the need for a unit that has responsibilities for this – drawing together relevant data, often drawn from different departments, keeping key politicians and civil servants informed, encouraging engagement in this by different sectors and departments and consulting with key stakeholders (Roberts 2010, Brown et al. 2012).

8.3.2. Development Plans and Pathways

As AR4 emphasized, many of the forces shaping greenhouse gas emissions are those underlying development pathways – including the scale, nature and location of private and public investment in infrastructure (Wilbanks, Romero Lankao et al. 2007). These also influence the form and geography of urban development and the scale and location of climate-related risks to urban buildings, enterprises and populations. Responsibility for encouraging new investments and migration flows away from high risk sites is often shared between local, provincial and national government through a combination of climate sensitive disaster risk management and urban planning and zoning. But the priority given by national and urban governments to economic growth usually means that this is rarely implemented with vigour (Douglass 2002, Reid et al, 2013).

8.3.2.1. Adaptation and Development Planning

Urban adaptation is becoming important for some national, regional and city governments although the first steps may have come from stakeholders outside the state sector. In high-income countries, interactions between national climate policies and local level and the division of responsibilities have been examined (see, for instance, Massetti et al 2007 for Italy). There is also attention to local adaptationimplementation through subsidies and flexible schemes in different city contexts and the transfer of authority and resources to city level (for the Netherlands see Gupta et al. 2007). The design of new decision making strategies for local governments considers the complexity and dynamics of evolving social-ecological systems (Kennedy et al. 2010). Examples include adaptation plans and local responses in Sydney to cope with sea level rise and storms (Hebert and Taplin 2006) and adaptation planning in California (Bedsworth and Hanak 2010). In China, adaptation programmes are being developed and implemented at national and local level. The debate emphasizes the policy space and the division of responsibility between national and local levels (Teng and Gu. 2007).

Since AR4, there has been a growing literature on urban adaptation in low and middle-income nations. A review of the literature on climate change impacts and adaptation in cities (Hunt and Watkiss 2011) could draw on eight case studies in Asia, five in Africa and four in South America – as well as from case studies from Europe, Northern America and Australasia. Among the papers and books considering climate change adaptation in urban areas since 2007 are those on Cape Town (Mukheibir and Ziervogel 2007, Ziervogel et al 2010 and Cartwright et al 2012), Durban (Roberts 2008a, 2010, Roberts et al 2012, Cartwright et al 2013 and Roberts and O'Donoghue 2013) and other urban centres in Africa (Douglas et al., 2008, Wanget al 2009, Lwasa 2010,World Bank 2011, Kithiia and Lyth 2011, Adelekan 2012, Kiunsi 2013, Castán Broto et al 2013, Silver et al 2013), urban centres in Bangladesh (Alam and Rabbani 2007, Jabeen et al 2010, Banks et al 2011, Haque et al 2012, Roy et al 2013), India (Revi 2008,Sharma and Tomar 2010, Saroch et al 2011), Latin America (Hardoy and Pandiella 2007, Romero Lankao 2007, 2010, Hardoy and Romero Lankao 2011, Luque et al 2012, Hardoy 2013, Hardoy and Ruete 2013). Other papers or books with discussions of urban adaptation in low- and middle nations include Blanco 2007, Carolini 2007, Martine et al. 2007, McGranahan et al. 2007, de Sherbinin et al. 2007, UN-Habitat 2007, United Nations Population Fund 2007, Agrawala and van Aalst 2008, Bartlett 2008, Ayers 2009, Bicknell et al. 2009, Kovats and Akhtar 2008, Tanner et al., 2009, Hardoy and Pandiella 2009,Wong 2009, World Bank 2010b, 2010c, 2011, Manuel-Navarrete et al. 2011, UN-Habitat 2011a, Rosenzweig et al 2011a, Moench et al 2011and Bulkeley and Tuts 2013. Four relevant issues can be highlighted: the fact that these nations have most of the world's current and future

urban population; the need to consider key development issues of poverty and social inequality as multidimensional problems that may be aggravated by climate change; the need to consider human agency among low-income inhabitants and their organizations as an important resource in building local responses to climate change; and the relevance of well-funtioning multilevel governance in developing adaptation strategies (Sánchez-Rodríguez 2009).

Although few publications suggest specific operational strategies, they stress the importance of the linkage between climate adaptation and development. We noted already how development deficits in urban areas can contribute to adaptation deficits. Manuel-Navarrete et al. (2011) explores the interplay between visions of development, governance structures and strategies to cope with hurricanes in the Mexican Caribbean where exposure and vulnerability are influenced by political decisions and contingent development paths. Similarly there are few reports on multidimensional approaches to guide operational adapation. There is growing attention to integrating adaptation with development interventions and addressing structural drivers of social and urban vulnerability – see for instance Climate Action Plans of Mexico City, Cartagena and San Andrés de Tumaco (Sánchez-Rodríguez 2009).

Two factors help explain the lack of detailed attention to urban climate change adaptation in low- and middle-income nations. The first is the lack of attention to urban adaptation within national policies on climate change in comparison with sectors like agriculture. Responsibility for climate change policies is often with ministries or agencies that have little in their work that is urban and little influence on others whose cooperation is essential e.g. for social policies, public works and local government (Ojima 2009, Roberts 2010, Hardoy and Pandiella 2007). Governments' social policies and priorities influence the social and spatial distribution of climate related risk and vulnerability – for instance provisions for health care, emergency services and safety nets - yet few agencies recognize their potential role in reducing risk and vulnerability. Adaptation in informal settlements and the incorporation of individual and group agency in bottom-up adaptation strategies is of particular relevance in low-income and most middle-income nations (Sánchez-Rodríguez 2009, Bicknell et al 2009). Recent experiences of Central American cities like Tegucigalpa and in some cities in the Philippines show that the involvement of low-income communities in risk reduction may be the first steps towards climate change adaptation (Aragón-Durand 2011, Carcellar et al. 2011).

The second factor explaining the lack of attention to urban adaptation is that the initial focus for many cities was on mitigation, in part because international support was available for this (although this is changing). Local decision-makers frequently view climate change as a marginal issue, with adaptation usually ranked lower than mitigation on the urban policy agenda (Bulkeley 2010, Simon 2010). For instance, Mexico City's climate change agenda focuses on mitigation with adaptation still a vague concept that is not incorporated into concrete actions and decisions (GDF 2006, 2008). Adaptation is seen as a capacity to withstand weather-related impacts such as floods through early warning systems rather than comprehensive, long-term measures such as watershed management to reduce the speed and volume of flood waters. There is little academic and policy literature on climate change adaptation for Brazilian cities (Ojima 2009, Soares Moura da Costa 2009). In Sao Paulo, more attention has been given to mitigation with adaptation action limited to broad declarations about needed actions in different sectors even as the city often gets impacted by floods, landslides and water scarcity (Puppin de Oliveira 2009, Nobre et al 2010, Martins and Ferreira 2011). The pressure on national and local governments to act is lessened by the absence of public awareness of the importance of addressing climate change adaptation (see Nagy et al. 2007). There is also a "knowledge gap" between policymakers and scientists regarding knowledge needed to enhance adaptation as in the case of Tijuana (see Sanchez-Rodríguez, 2011).

8.3.2.2. Disaster Risk Reduction and its Contribution to Climate Change Adapation

The growing concentration of people and economic activities in urban centres and the increasing number and scale of cities can generate new patterns of disaster hazard, exposure and vulnerability. This trend is visible in the large and rising number of localized disasters in urban areas in many low- and middle-income nations, mainly associated with extreme weather (storms, flooding, fires and landslides) (United Nations 2009, 2011). This has particular relevance for climate change adaptation, given the increase in the frequency and intensity of potentially hazardous weather events that climate change is bringing or may bring. Extreme weather events have also helped raise the awareness of citizens and local governments of local risks and vulnerabilities.

Exposure to disaster risk from weather events in expanding urban areas increases when local governments fail to implement their responsibilities, including needed expansion or upgrade in infrastructure and services and risk reduction through implementing building standards and appropriate land-use management (ibid). This is typically in countries with low per capita GDPs and weak local governance (i.e., in the first two categories of Table 8-2). It may be exacerbated by rapid urban population growth.

The most urbanized nations generally have the lowest mortality to extreme weather events (United Nations 2009). Urbanization accompanied by more capable and accountable local governments can reduce disaster risk as is evident in the declines in mortality from extreme weather (and other) disasters in many middle and all high-income nations (United Nations 2011).

While local government investment usually represents a small proportion of total investment in and around an urban centre, it has particular importance in risk reduction through investments in risk-reducing infrastructure and public services that need to be combined with planning and regulation that ensures buildings and infrastructure meet needed standards and guide development away from high-risk areas. Urban governments have explicit responsibilities for many assets, some of which may be risk prone. The exact list differs between countries because of different allocations of responsibilities between government levels but it often includes schools, hospitals, clinics, water supplies, sanitation and drainage, communications and local roads and bridges. Where private provision for infrastructure and services is significant, it usually falls to local government to coordinate such provision and hence, enhance its role and responsibility for urban adaptation.

From the late 1980s, a new approach to reducing disaster risk in urban areas was developed in some Latin American nations that is relevant to climate adaptation. It involved three processes: detailed analyses of local records of disasters that include smaller disaster events than those reported in international databases; recognition that most disasters were the result of local failures to assess and act on risk; and the recognition of the central roles of local governments in disaster risk reduction but with support from national and local civil defence organizations working with civil society and community organizations within the settlements most at risk (United Nations 2009, IFRC 2010). These led to institutional and legislative changes at national or regional level to support disaster risk reduction (Gavidia 2006, IFRC 2010). In Colombia, a national law supports disaster risk reduction and a National System for Prevention and Response to Disasters with a shift in the main responsibility for action to municipal administrations. In Nicaragua, the National System for Disaster Prevention, Mitigation and Response (SINAPRED) was set up in 2000 to work with local governments to strengthen disaster preparedness and management by integrating disaster mitigation and risk reduction into local development processes (Von Hesse, et al., 2008). There are other initiatives and action programmes in Central and South America on urban risk management and disaster preparedness, including the influence of La Red (IFRC 2010), the DIPECHO project, “Developing Resilient Cities” and UNDP and GOAL in Central America.

In growing numbers of cities in Asia (Shaw and Sharma, 2011) and Africa (Pelling and Wisner 2009), experiences with community-driven ‘slum’ or informal settlement upgrading has led to a recognition of the potential of these to reduce risk and deep rooted vulnerability to extreme weather events. This is most effective when supported by local government and civil defence/emergency response agencies (see Boonyabancha 2005 for urban centres in Thailand; also Archer and Boonyabancha 2011, Carcellar et al. 2011).

The Homeless People’s Federation of the Philippines developed a series of effective responses following major disasters, which included: community-rooted data gathering (assessing the severity and scope of destruction and victims’ immediate needs); trust and contact building; support for savings; the registering of community organizations; and identifying needed interventions, including building materials loans for house repairs. The effectiveness of risk reduction is also much enhanced where local governments work to support these (Carcellar et al. 2011) and experiences such as these have helped inform community-based adaptation (see 8.4).

There are also international networks supporting innovation in disaster risk reduction and/or climate change adaptation and inter-city learning. These include la Red in Latin America that has been operating for 3 decades (IFRC 2010), the Earthquakes and Megacities project which includes multi-hazard risk assessment and the cities

programme of the Asian Disaster Preparedness Centre. As donor interest has grown in supporting disaster risk management as a vehicle for climate change adaptation, a number of resilience oriented urban programmes have developed including the Asian Cities Climate Change Resilience Network (Brown et al. 2012), the UN ISDR Resilient City network (Johnson and Blackburn,2013) ICLEI's city adaptation network and UN-Habitat's Cities and Climate Change Initiative.

Despite growing international support for urban disaster risk management, it can be difficult for local governments to access the human and financial resources needed to make real change on the ground (Von Hesse et al. 2008). Local governments do not get recognition for the disasters their programmes prevented – so risk reduction investments are not seen as priorities and have to compete for scarce resources with what are judged to be more pressing needs. Effective policies are often tied to the terms in office of particular mayors or political parties (Mansilla et al. 2008, Hardoy et al. 2011). In most cases, disaster risk reduction is still not integrated into development plans and not drawing in all relevant departments and divisions of local government. Manizales in Colombia is an exception as disaster risk reduction has long been seen as part of local development and where collective interests overcome individual and party political interests (Hardoy and Velásquez Barreto 2014)

As detailed in IPCC SREX (2012), disaster risk management is increasingly positioned as a frontline sector for the integration of climate change adaptation into everyday decision-making and practices. This can be seen in the plans of municipalities such as Tegucigalpaand Montevideo (Aragón-Durand 2011). Where disaster risk management is taken seriously by government or civil society this offers real opportunities for synergy as the long-range nature of climate change concerns and its policy visibility can enhance local support for disaster risk management. The still common disjuncture in international frameworks and national responsibilities mean there is much scope for better coordinated efforts to make urban disaster risk management climate smart (SREX 2012, Aragón-Durand 2008).

8.3.3. Adapting Key Sectors

8.3.3.1. Adapting the Economic Base of Urban Centres

8.2 described how climate change will bring changes to the comparative advantages of cities and regions – for instance through influencing climate sensitive resources and changes in locations of extreme weather, water availability and flooding risks. Many case studies show how extreme weather and storm surges can impede economic activities such as damaging industrial infrastructure and disrupting coastal ports and supply chains (see 8.2.3.4).Vugrin and Turnquist (2012) discuss how to design for resilience in infrastructure distribution networks such as electric power, gas, water, food production and manufacturing supply chains. Increasing the resilience of networks (and settlements) needs absorptive capacity (for instance to withstand extreme weather), adaptive capacity (for instance service provision through alternative paths) and restorative capacity (quick and cheap recovery).

The importance of effective climate adaptation is that it can help reduce risks from such changes, deepen resilience and limit disadvantages. For urban centres facing climate-related risks, a failure to adapt may discourage new investments. Over the long term this could lead enterprises moving or expanding to other safer, better adapted locations. Multinational corporations and many national businesses have long been adept at changing the location of their production (and regional headquarters) in response to changing opportunities and risks so they can choose to avoid urban centres facing high risks linked both to climate change and a failure to adapt. Investments in urban centres with higher risks may also be discouraged by high insurance costs,

Disasters can change perceptions of risk and discourage new investments. For instance, businesses may avoid disaster impacts in their own facilities but find that the disaster has impacted other businesses and services that they use (including utilities) or impacted their workforce and the services they use (including schools, and hospitals) (Hallegatte et al, 2011). A lack of capacity within an urban centre to reconstruct means increased vulnerability to succeeding extreme weather events and less new investment that in turn weakens the urban economic base (Benson and Clay 2004, Hallegatte et al. 2007, Hallegatte et al. 2011).

Past experience of de-industrialization in cities in the U.S. and Europe show the difficulties facing city governments in attracting new investment. When the main activity of a city or region weakens, incomes, employment and local authority revenues decrease, making it more difficult to re-invest in new business and reducing attractiveness for new investments. If climate change forces many regions to change their economic structure and business models, transitions may prove difficult to manage (Berger 2003). Specific adaptation policies may be useful to help make the transition more rapid and less painful.

Climate change adaptation is generally cheaper and easier to implement in greenfield sites – for instance as low-risk sites are chosen, trunk infrastructure to appropriate standards installed and building and land-use regulations enforced. Retrofitting existing infrastructure and industries is generally more expensive (McGranahan et al.,2007).

Within and around urban centres, local governments may need to utilise several strategies to strengthen urban centres' resilience including selective relocation, land use planning to reduce exposure, shifting development from floodplains, and revised building regulations to retrofit or flood-proof structures (Hanson *et al*. 2011). There are also synergies to be encouraged in peri-urban or nearby rural areas where land-use management around a city supports rural livelihoods (and where appropriate urban agriculture and forestry) and protects ecosystem services (see 8.3.3.7). There may be opportunities for proactive adaptation outside larger cities where much of the future urban growth will occur. For instance, in Manizales, Colombia, local government has begun incorporating climate change and environmental management into its local development agenda, including the establishment of city climate monitoring systems, although this is a city that has long had innovative environmental and disaster risk reduction policies (Hardoy and Velásquez Barreto 2014). However, smaller urban centres are often institutionally weaker and lack investment capacity and critical infrastructure.

Adapting the urban economic base may require short- and long-term strategies to assist vulnerable sectors and households. The consequences of climate change for urban livelihoods may be particularly profound for low-income households who generally lack assets or insurance to help them cope with shocks (Moser and Satterthwaite 2008). For most urban centres, the informal sector is a significant part of its economy and provides employment for large sections of the population. But the effects of extreme weather on the informal economy are rarely considered as in the case of 2003 floods in Santa Fe, Argentina (Hardoy and Pandiella 2009). One example where it was considered was in Kelurahan Pabean Pekalongan in Central Java where batik production provides livelihoods for three quarters of adults and this is disrupted by floods that residents suggest are becoming increasingly frequent (UN-Habitat 2011b). Cash transfers and safety nets for vulnerable groups and those with inadequate incomes may be needed to help them cope with the short-term impacts of climate change (Sánchez and Poschen 2009) as well as climate variability. But these do not address the risks they face or support the needed collective or public investments in risk-reducing infrastructure and services (Mitlin and Satterthwaite 2013).

There is a growing discussion and literature of the importance of support for a 'green economy' combined with green infrastructure to help shift nations' economic and employment base towards lower carbon, more climate resilient patterns that also respect regional and global ecological and resource limits. For urban centres, this seeks to highlight new business opportunities as it requires existing and new businesses and employment opportunities to help limit anthropogenic climate change, resource depletion and environmental degradation. Other goals are sometimes added – for instance also supporting social inclusivity and eco-efficiency as mutually reinforcing principles (e.g. Allen and Clouth, 2012). The literature has begun to explore the changes that are needed in production systems (especially in regard to carbon intensity, waste generation and management), buildings, transport systems and electricity generation and in consumption patterns by wealthier groups (Hammer,*et al*. 2011, UNEP 2011a and b, UN-Habitat 2012 a,b,c and d, World Economic Forum 2013). But as yet, there is too little detailed discussion of how a green economy can be fostered in relation to particular cities or in regard to the incentives and regulations needed to shift private investment to this.

The 'waste economy' in cities in low- and middle-income nations should be an important sector in the green economy as it provides livelihoods to a large number of people (Hasan et al 2001, Hardoy et al. 2001, Medina 2007) along with contributing to waste reduction and GHG emission reduction (Ayers and Huq 2009). In Brazil's main cities, over 0.5 million people are engaged in waste picking and recycling (Fergutz et al. 2011); an estimated 17,000 people in Lima and 40,000 in Cairo earn their livelihoods from informal recycling (Scheinberg et al.2011). The

mechanisms by which city governments choose to work with those working in this waste economy or ignore them have obvious implications for employment and for resource use.

For some cities, there is documentation of the kinds of adaptation needed to protect or enhance their economic base. For instance, in Mombasa, local authorities may need to redesign and reconstruct the city's ports, protect cement industries and oil refineries and relocate some industries inland, all of which requires major capital investments (Awuor et al. 2008).There are many parts of Rio de Janeiro's diverse economy (including manufacturing, oil refineries, shipyards and tourism) that adaptation will need to protect along with the urgent need to address the vulnerability of large populations living in informal settlements (favelas) on land at risk of landslides (de Sherbinin et al. 2007). Defences needed to help safeguard coastal industries and residential areas could threaten the city's beach tourist industry and cause further erosion to other unprotected areas. It is also difficult to focus the attention of politicians and civil servants on adaptation when their planning for city development is focused on hosting the World Cup and the Olympics. As in most cities, making Rio's economic base more resilient to climate change will need to resolve such tensions and trade-offs, necessitating dialogue amongst local stakeholders (Ruth 2010).

As yet, there is little evidence that climate-change related risks or cities' adaptive capacities have an influence on the location of private sector investments. They are however, influenced by the availability of infrastructure and services that are an essential part of adaptive capacity. Many cities in Asian high growth economies are located in low-elevation coastal zones which are undergoing rapid urbanisation and economic transformation (McGranahan et al., 2007).Many of these coastal settlements are also within areas where cyclones are common. Without adaptive measures and with rising concentrations of population, infrastructure, and industries along India's coasts, there could be a non-linear increase in coastal vulnerability over the next two decades (Revi 2009). The same is true for China (McGranahan et al. 2007). In most nations, urban governments have found it difficult to prevent new developments on sites at risk of flooding, especially where these are attractive locations for housing or commerce; this is even when there is legislation and plans to that regulate land use (see Olcina Cantos et al 2010 for a study of this in Alicante in Spain)

Few economic assessments of climate change risks have been completed in West African coastal cities. National and city governments will face difficulties protecting many cities or particular districts and their industries, infrastructure and tourism as in the case of Cotonou (Doussou and Gléhouenou-Doussou 2009) . Lagos, Dakar, and other important economic centres in the Gulf of Guinea have large areas on the coast that are close to mean sea level, leaving them highly vulnerable to erosion and rising sea levels (Simon 2010). Compounding the climate change-induced flooding risks are the cities' rapid coastal construction, destruction of mangrove swamps, and inadequate refuse collection (ibid.).

8.3.3.2. Adapting Food and Biomass for Urban Populations

Large sections of the urban population in low- and middle-income countries suffer hunger while a larger number face food and nutrition insecurity (Montgomery et al. 2004, Ahmed et al. 2007, Cohen and Garrett 2010, Crush et al., 2012). This is due more to their low incomes and limited capacities to access food than to overall food shortages (Cohen and Garrett 2010, Crush et al.,2012). Among low-income urban households in such nations, food expenditures generally represent more than half of total expenditures (Cohen and Garrett 2011). This makes them particularly at risk from food price inflation.

Climate change impacts can have far-reaching influences on food security and safety, but these "will crucially depend on the future policy environment for the poor" (Schmidhuber and Tubiello 2007: 708, see also Douglas 2009). Globally, agriculture has managed to keep up with rising demands worldwide, including the rapid growth in the population, the rapid increase in the proportion of non-agricultural workers to agricultural workers that accompanies urbanisation and consumer dietary shifts that are far more meat and carbon intensive and often land intensive (Satterthwaite et al. 2010). However, food security may be eroded by competing pressures for water or bio-fuels (Godfray *et al,* 2010). Although adjustments in farming practices are essential, adapting urban food systems represents a major challenge and will necessitate radical changes in food production, storage, processing, distribution, and access (ibid).

Urban food-related adaptation needs to consider both supply and demand side constraints. Climate-change related constraints on agricultural production and the food supply chain can impact urban consumers through reduced supplies or higher prices. Falling agricultural production or farmer incomes also reduces their demand for the urban producer and consumer goods and services they use. Disruption to urban centres may also mean disruption to the markets, services or remittance flows on which agricultural producers rely (Tacoli 2003). Thus, food policies for climate change adaptation need to take account of complex rural-urban linkages (Revi 2009). Thus, a portfolio of responses that can bridge rural and urban boundaries, as well as action at the household, local, national, and international levels, is needed to strengthen urban food security.

Urban centres that are seriously impacted by extreme weather also face serious challenges in ensuring that the affected population have access to adequate and safe food and water supplies. Flooding, drought, or other extreme events often lead to food price shocks in cities (Bartlett 2008) as well as spoiling or destroying food supplies for many households. After the 2004 floods in Bangladesh, Dhaka's rice prices increased by 30 percent and vegetable prices more than doubled (Douglas 2009**).** Bangladesh's urban slum-dwellers and rural landless poor were the groups worst-affected by food insecurity (*ibid*.).

When facing increased food prices, the urban poor in low and most middle-income nations adopt a range of coping strategies such as reduced consumption, fewer meals, purchasing less nutritious foods, or increasing income earning work or work hours, particularly by women and children (Cohen and Garrett 2011). But these erode nutrition and health status, especially of the most vulnerable and fail to strengthen resilience, particularly in the context of more frequent disasters.

Adaptive local responses have included support for urban or peri-agriculture, green roofs, local markets and enhanced safety nets. Food price increases may be moderated by improving the efficiency of urban markets, regulations to promote farmers' markets, or investing in infrastructure and production technologies (Cohen and Garrett 2011). Food security may be enhanced by government support for urban agriculture and street food vendors (ibid., Lee-Smith 2011**).** Food security for urban dwellers with low incomes is also increased if they have access to cheaper food or to social incomes – for instance cash transfers (e.g. Brazil's Bolsa familia programme) or, for older groups pensions (Soares et al. 2010). While initially rural-focused, cash transfer programmes have been expanded in urban areas and in some nations reach a large proportion of the low-income urban population (Johanssen *et al*. 2009, Niño-Zarazúa 2010**,** Satterthwaite and Mitlin 2013).

8.3.3.3. Adapting Housing and Urban Settlements

Urban adaptation will be built on the bedrock of good quality and affordable housing that conforms to appropriate health and safety and climate-resilient building standards and has sufficient residual structural integrity over its service life to protect its occupants against extreme weather (United Nations 2009, 2011).

Section 8.2.4.4 noted how poor quality housing is often at risk from extreme weather. Its resilience can be enhanced via a range of structural interventions (for instance retrofitting existing buildings and revising standards for new-build), interventions that reduce risks (for instance expanding drainage capacity to limit or remove flood risks) and non-structural interventions (including insurance). The need for attention to all three of these are obviously greatest where housing quality is low, where settlements have developed on high-risk sites and for cities in locations where climate change impacts are greatest. However, enhancing the resilience of the buildings that house low-income groups also faces many political challenges (see Roaf et al., 2009).

Most of the city governments that have developed climate change adaptation strategies include measures to adapt the building stock. But even in the cities with such discussions, there is still a need to act on the risks and vulnerabilities identified. The range of actors in the housing sector, the myriad connections to other sectors and the potential to promote mitigation, adaptation and development goals all suggest the need for well-coordinated strategies that can support resilience (Maller and Strengers 2011).

An increasing number of cities have undertaken or commissioned studies to identify measures needed to adapt housing (and other buildings) although there is less evidence of the detailed action plans, budget commitments and regulation changes needed to implement them. A climate change assessment for Bangkok Metropolitan Administration identified a range of measures including a need to flood-proof homes, build elevated basements, and relocate power-supply boxes upstairs; also for households to maintain sufficient food, water, fuel, and other supplies to ensure 72 hours of self-sufficiency (BMA and UNEP 2009). It also pointed to regulatory changes that may be needed to bolster resilience including land use restrictions in floodplains and other at-risk sites and revised safety and fire codes for buildings and other structures (ibid). Cape Town's climate change framework (2006) proposed housing interventions including improving construction and regulations for building informal housing, in part to reduce the need for emergency response and anticipate projected climate change. Regulations in New York and Boston are being updated to address climate-related risks to the built environment (see Boston 2011, PlaNYC 2011). London and Melbourne's adaptation plans discuss climate-related impacts on the housing sector, as well as detailing extensive adaptation measures. London's draft plan considers management strategies at city level, neighbourhood, and building scale, which combine green infrastructure and housing interventions (GLA 2010). Approved in 2009, Melbourne's plan similarly combines housing, water, and green infrastructure strategies to promote cooling and long-term adaptation (UN-Habitat 2011a).

Housing and extreme heat:More attention is being paid to understanding and addressing risks from extreme heat in particular cities – see for instance Chicago 2008 and 2010, Tomlinson et al 2011 for Birmingham, Matzarakis and Endler 2011 for Freiburg and Giguère 2009 for Quebec. Attention is needed to buildings that provide protection from heat waves, especially in urban heat islands and for populations that are more vulnerable to extreme heat. In locations that have large daily variations in temperature, this includes upgrading homes with limited ventilation and with low thermal mass. Interventions that reduce heat gain are also needed including passive cooling and other design measures (Roberts 2008b, Hacker and Holmes 2007) as well as modifications to buildings and open spaces in areas that are heat islands (see later discussion on green and white roofs).Chicago's 2008 Climate Action Plan discussed the need to "pursue innovative cooling," which will "seek out innovative ideas for cooling the city and encourage property owners to make green landscape and energy efficiency improvements" (Chicago 2008: 52). Air conditioning and other forms of mechanical cooling can provide relief but these are too expensive or not available for the many urban households with no electricity supplies. They are also mal-adaptive if they rely on electricity whose generation is contributing to greenhouse gas emissions. Residents' vulnerabilities may be exacerbated if electricity supplies are unreliable and "if blackouts occur on the hottest days when peak demand is at its worst" (Maller and Strengers 2011: 3). To date, the literature on adapting housing and neighbourhoods to extreme heat focuses on cities in high-income nations although many of the cities already experiencing periods of extreme heat are in low- and middle-income nations.

Passive cooling can be used in both new-build and retrofitted structures to reduce solar gain and internal heat gains, while enhancing natural ventilation or improving insulation (Roberts 2008b and 2008c). Although developments such as the Beddington Zero Energy Development (BedZED) in London (Chance 2009) or Germany's PassiveHaus standard (Rees 2009) have set precedents for mitigating household emissions, these passive designs can simultaneously contribute to adaptation. The designers of BedZED sought to reduce energy demand for heating, cooling and ventilation while also utilising super-insulation, ventilation, and other measures to ensure energy is not required for most of the year (Chance 2009). Thermal mass can be used for residential cooling, "because it introduces a time-delay between changes in the outside temperature and the building's thermal response necessary to deal with the high daytime temperatures" (Hacker and Holmes 2007: 103). Structures in southern Europe already utilise solar shading, ventilation, and thermal mass in the building fabric to promote cooling (ibid.). Simulations for London buildings (under UKCIP02 Medium-High emissions scenarios) suggest that utilising shade, thermal mass, control of ventilation and other advanced passive designs are an "eminently viable option for the UK, at least over the next 50 years or so" (*ibid.,* : 111). Nevertheless, there are several obstacles to the incorporation of passive designs. Opening windows may be hampered by security concerns or noise pollution in cities (Hacker and Holmes 2007). Modern windows "often do not ventilate well," and site restrictions, cost, or other constraints may impede the use of passive cooling "particularly in the refurbishment of existing buildings" (Roberts 2008b: 4554).

Housing and disaster-preparedness measures:If populations are displaced by disasters or need to be evacuated temporarily from their homes, provision for emergency shelters and services need to be able to respond with

particular attention to vulnerable residents. For instance, housing agencies established shelters and recovery centres after Cyclone Larry in Queensland (in 2006) and New South Wales' coastal flooding (in 2007). Interviews with officials recalled the strains facing 24-hour providers in the shelters and coordination difficulties with emergency health workers, police, insurance, and other agencies (Jacobs and Williams 2011). While not addressing climate change explicitly, the study helps highlight the range of social support, structural strategies, and interagency efforts that local authorities may need to develop to adapt to climate change. For many urban centres, there is also the issue of how to move populations at risk when needed (and to get their agreement to do so) and this presents many challenges (Roaf et al., 2009).

Urban centres facing extreme heat need heat-wave plans that warn citizens of what is anticipated and what measures they can take and ensure adequate water provision, emergency healthcare, and other public services that focus on vulnerable residents. This includes special attention to infants and to the elderly in hospitals, residential facilities (Hajat et al. 2010, Brown and Walker 2008) or living alone. It should include back-up electricity although large sections of the urban population in low- and middle-income nations do not have electricity (Johansson et al., 2012) and this also means no access to devices that help with cooling. Here too, the examples of cities with responses to heat waves that focus on those most at risk (see for instance Toronto 2012) are mainly from high-income nations.

8.3.3.4. Adapting Urban Water, Storm, and Waste Systems

The challenge of this section (and this chapter), is summarizing key adaptation issues drawn from examples that come from a highly heterogeneous mix of urban areas across the globe with order of magnitude variations in the quality and extent of provision for water, sanitation and drainage. In high-income and some middle-income nations, virtually all the urban population is served by drinking quality water piped to the home 24 hours a day, by sewers or other systems of sanitation that minimize risks of faecal contamination and by storm and surface drainage. As noted in 8.2, there are many urban centres in such nations that face serious climate change-related challenges for water. But their plans do not have to address the fact that a significant proportion of their population do not have piped water or toilets in their homes, or storm drains. They also have in place billing systems that generate a substantial proportion of the funds needed for water provision and management.

At the other extreme are a very large number of urban centres in low-income and middle-income nations with very large deficits in provision for water, sanitation and drainage and with weak, under-resourced institutions (UN Habitat 2003, WHO and UNICEF 2012). There is also the billion or so people living in informal settlements where authorities or companies responsible for water and sanitation provision are often unwilling to invest or not allowed to do so. In considering how to adapt water and waste water systems to climate change, there are not only large differences between nations and cities in the scale and nature of likely impacts but also in the quality and extent of provision and resources available to local water and sanitation providers. New York City can develop a ten billion dollar plan to assure it receives adequate water supplies (Solecki 2012) while many cities in sub-Saharan Africa not only have very large deficits in piped water provision, sewers and drains but also very limited investment capacities (see for instance Kiunsi 2013 for Dar es Salaam).

Some studies have sought to estimate the costs of adapting urban water and sanitation systems. Muller 2007 discusses the direct and indirect impacts of changes in rainfall patterns and stream flows on sub-Saharan African cities. He suggests that $1-2.7 billion is needed annually to adapt existing urban water infrastructure and this does not include the cost of addressing deficient infrastructure. Another $1-2.6 billion a year is needed to adapt new developments (including water storage, waste-water treatment and electricity generation). Other research also suggests significant investments needed in low- and middle-income nations to overcome current shortfalls in water and sanitation as well as to cope with climate change (Arnell et al. 2009).

8.3.3.4.1. Adapting urban water supply systems

Major et al (2011) lists a range of cities that have begun to plan for and adapt water systems and other infrastructure including Boston, London, Halifax (Canada), New York, Seattle and Toronto. For cities with climate change

adaptation plans, water and waste water management are usually important components (see for instance Helsinki Region Environmental Services Authority 2012). But developing such measures is not yet commonplace.

Supply-side approaches to seasonal water shortages such as increasing reservoirs are frequently advocated. An analysis of 21 draft Water Resources Management Plans in the UK found that agencies usually favoured reservoirs and other supply-side measures to adapt to climate change (Charlton and Arnell 2011). The authors suggest that additional demand-side interventions may be needed to cope with reductions in water availability. Although based upon draft plans from 2008 rather than implemented strategies, the study indicates some key trade-offs and a portfolio of responses currently under consideration. To expand its reservoir capacity, Rotterdam developed plans that combine the goals of adaptation and urban renewal (van der Brugge and de Graaf 2010). Floods in 1998 exposed the inadequacies of existing water infrastructure, particularly in the context of climate change, and municipal water authorities committed to expand retention capacity by mixing economic activities with water-based adaptive designs, including 'water retention squares' and green roofs; floating houses; and networks of channels. Seattle has utilised demand-side strategies to curtail water consumption including aggressive conservation measures, system savings and price increases linked to consumption levels (Vano et al. 2010). A simulation exercise suggested the system can withstand climate change-induced alterations in reservoir inflows, and the authors note that the "primary reason" for such robustness is the successful reductions in demand (ibid. p. 283).

In Mexico City, government programmes on climate change have suggested actions regarding the water sector although some of these have been proposed many times since the 1950sbut not acted on. These include measures to decrease water use and the restoration and management of urban and rural micro-basins (Romero-Lankao 2010). Since these programmes prioritize mitigation over adaptation, adaptation measures for the water sector have been conceived as too general and with a lack of institutional commitment. In Durban, the importance of getting climate change adaptation within the water sector was recognized as a priority – and the water sector is influential within the city government because of its importance in delivering development benefits and also it is revenue-earning, well-resourced and retains skilled staff (Roberts 2010). The water sector has also shown an interest in developing its municipal adaptation programme (ibid).

Cape Town faces profound challenges in ensuring future supplies (Mukheibir and Ziervogel 2007). The city responded by commissioning water management studies, which identified the need to consider stresses including climate change as well as population and economic growth (*ibid*.). During the 2005 drought, the local authority substantially increased water tariffs, and such mechanisms may represent "one of the most effective ways" to promote efficient water usage (Mukheibir 2008: 1271). Additional measures may include water restrictions; reuse of grey water; consumer education; or technological solutions such as low-flow systems or dual flush toilets (*ibid*).

Research in Phoenix, Arizona sought to improve water forecasting data and inform adaptation interventions (Gober et al.2010). This rapidly-expanding desert city is projected to reach 11 million people by 2050, with most growth in peripheral areas that depend on groundwater (Bolin et al.2010). Simulations explored how water usage may be reduced to achieve safe yield while accommodating future growth (ibid). Reducing current high per capita water use may be achieved through urban densification, increased water prices and water conservation measures (ibid). Gober et al 2010 agree that stringent demand and supply policies can forestall "even the worst climate conditions and accommodate future population growth, but would require dramatic changes to the Phoenix water supply system" (ibid: 370).Quito's local government has formulated a range of adaptation plans to address water shortages (Hardoy and Pandiella 2009). The city is projected to experience reduced freshwater supplies as a result of glacier retreat and other impacts of climate change. Among the municipality's responses are developing dams; encouraging a culture of rational water use; reducing water losses; and developing mechanisms to reduce water conflicts (ibid.). However, Quito has not sought to incorporate community participation in planning and implementation (ibid.). Participatory water planning has occurred elsewhere in Latin America: stakeholders in Hermosillo, Mexico, identified and prioritized specific adaptations such as rainwater harvesting and water-saving technologies (Eakin et al.2007).

Several cities are considering the potential of rainwater harvesting to enhance water supplies. In Sydney, new houses are required under a 2004 law to save 40% of reticulated water for use in gardens and toilets and subsidies were available to install household roof tanks (Warner 2009: 235). Many low-income Caribbean households rely on rainwater collection systems for domestic use, yet upper-income groups in Barbados have voiced resistance to the

practice (Cashman et al. 2010). Extending existing communal collection and distribution systems would require community financing or governmental interventions, as well as overcoming such resistance *(ibid.)*.

8.3.3.4.2. Waste and storm water management

Most of theadaptations mentioned above are to help ensure sufficient water supplies. Less attention has been given to adaptations needed in sewer and drainage systems whose capacities will often need to be increased substantially and, for coastal cities, adapted to allow for the impacts of sea-level rise. We noted earlier the very large deficiencies in provision for drainage for urban centres in low- and many middle-income nations.

In St. Maarten, Netherlands Antilles, the government initiated a storm water modelling study and is developing a flood warning system (Vojinovic and Van Teeffelen 2007). Other options under consideration include institutional adaptations such as a new decision-support framework, centralised GIS to enhance all infrastructure planning measuresand public education, alongside structural measures such as improving the channel network and draining of areas with a high groundwater table (ibid).City management in Toronto, Canada has prioritised an upgrade of storm water and wastewater systems to circumvent the direct and indirect stresses from climate change (Kessler 2011). Deak and Bucht (2011) analyse past hydrological structures in the city of Lund, Sweden and use the concept of indigenous blue infrastructure to raise questions concerning current storm water management in the urban core. Cities in California have a range of flood management methods but will need to augment these with forward-looking reservoir operation planning and floodplain mapping, less restrictive rules for raising local funds, and improved public information on flood risks (Hanak and Lund 2012).

The last 20 years have seen more attention by most governments to water sector reform (UN Water 2012). Many have developed integrated water resource management (ibid) with linkages between provisions for water, sanitation and drainage and other sectors, This recognizes that water adaptation plans need to work with a range of partners, consider broader development goals, identify tensions or trade-offs and implement low-regret anticipatory solutions, For cities, this often has to include groundwater use management and water catchment management in areas that are outside their jurisdiction and thus collaboration with other local governments in integrated flood management (WMO 2009). Most examples of this are in high-income nations (for an exception see Bhat et al., 2013).

Urban water systems usually depend on reliable electricity supplies and can be energy intensive – for instance utilizing water from distant or low-quality sources that require high levels of energy for conveyance or treatment.Water adaptation planning will need to be developed in concert with energy conservation, water catchment management and green infrastructure strategies. Integrated strategies can minimize possible conflicts between water-intensive parks or gardens, support local industries, and ensure equitable access to water in cities.

8.3.3.5. Adapting Electric Power and Energy Systems

The heavy dependence of urban economies, infrastructure, services and residents on electricity and fossil fuels means far-reaching consequences if supplies are disrupted or unreliable (see 8.2.4.2). With the energy literature and urban energy policy discussions dominated by mitigation concerns, “relatively few assessments in the energy sector focus on adaptation issues” (Mdluli and Vogel 2010: 206; see also Carmin et al 2009). The UNFCCC’s estimates for investment to address climate change (UNFCCC 2007) did not estimate the costs of adapting the energy sector (Fankhauser 2010). Key issues relating to adaptation for the energy sector including electricity generation and distribution are usually national or regional and so are discussed in Chapter 10. But urban governments and urban dwellers’ responses still have importance. Research has suggested that “private autonomous measures will dominate the adaptation response as people adjust their buildings, [or] change space-cooling and -heating preferences...” (Hammer et al 2012,27) so this suggests a need for policies that encourage these measures to contribute to adaptation and mitigation and serve those with limited incomes. A few cities have adaptation initiatives underway for energy systems while some others have begun to consider the steps needed to adapt local energy systems (ibid).

The interrelations between energy and other sectors suggests the need for an integrated approach in understanding energy poverty and vulnerability to climate change and shaping appropriate responses (Gasper et al. 2011). One issue of relevance to urban households, businesses and institutions is the extent to which they will need autonomous provision or back-up generating capacity, if grid supplies become unreliable. This represents a high additional cost and less efficient electricity production. Another issue is the extent to which emergency services can function when energy supplies are disrupted.

There is also the adaptation agenda needed for industries related to the supply of fossil fuels that involve or should involve urban governments. For instance, in the State of Veracruz, Gulf of Mexico, cities such as Coatzacoalcos and Minatitlan are surrounded by oil, gas and petrochemical plants that can be affected by the impact of weather-related events REF. Even though there is a growing concern about the potential impact that climate change and extreme weather events will have in the oil industry in Canada, US and Mexico and how floods and sea level rise will disrupt oil, gas and petrochemical installations, few climate change adaptation studies on this theme have been undertaken.There are also important potential co-benefits between mitigation and reduced air pollution from thermal power stations, motorized transport and other industries.

8.3.3.6. Adapting Transport and Telecommunications Systems

Adapting urban transport and telecommunications systems to the many impacts of climate change (including rising average temperatures, more or more intense heat waves and storms and sea-level rise) poses many challenges (Mehrotra et al 2011b). Urban centres depend on road and often rail, air and waterway transport systems for daily functioning – including the movement in and out of the urban centre or core by commuters and consumers and daily deliveries. Many cities depend on underground electric rail systems which may be at considerable risk from flooding including New York and London (Eichhorst 2009).

The development of reliable low-cost transport has also increased the dependence of prosperous cities and businesses on regional, national and international supply chains; for instance, 80 percent of the food consumed in London is imported (Bioregional and London Sustainable Development Commission 2010). Most large and successful cities have also spread spatially with the expansion of transport systems supporting a decentralization of the workforce and businesses, most of which depend on a well-functioning transport system. The importance of adapting transport infrastructure to climate change is highlighted by the 60,000 jobs and US$ 3 billion worth annual movement of goods in the Great Lakes–St. Lawrence route in the USA (Ruth 2010). This includes a need to adapt to lower water levels. The study also notes the scale of indirect and direct job losses that could result from decreased connectivity of the shipping network (Ruth 2010).

Transport systems:Cities that have developed climate change adaptation plans usually include attention to more resilient transport systems (UN Habitat 2011a). Melbourne's adaptation plan notes that intense storms and wind may lead to blocked roads and disrupt traffic lights, trains, and trams and how the extent of the disruption may be "further exacerbated by any additional compounding factors such as large-scale events, power disruptions or emergency situations, such as multiple deaths or injuries" (Melbourne 2009:60).

Adaptation will require transport planners to account for climate uncertainties, utilise a whole-of-life approach to managing infrastructure, and constantly update risk assessments (Love et al. 2010: 144). An interdisciplinary approach can incorporate not only changing meteorological hazards but also consider the social and political values and governance framework that can shape more resilient transportation systems (Jaroszweski et al. 2010).

Adapting roads:Climate change may increase the costs of maintaining and repairing road transport networks (see Hayhoe et al. 2010 for a discussion of this for Chicago due to rising average temperatures and more severe rainfall). In Durban, "it may be necessary to revise road construction standards and avoid routes at high risk of flooding" (Roberts 2008a: 531). Coastal road adaptation may require strengthening barriers, increasing design parameters to cope with sea-level rise, or realigning existing roads to a higher location (Regmi and Hanaoka 2011).

To adapt road networks, transport planners are beginning to reassess maintenance costs and traditional materials – for instance stiffer bituminous binding materials to help cope with rising temperatures and softer bitumen for colder regions (Regmi and Hanaoka 2011: 28). However, current cost considerations may impede their use. The Chicago Department of Transportation decided not to use more permeable, adaptive road materials instead of asphalt and concrete because of higher cost, although it recognised costs may fall with greater economies of scale as demand rises for such materials (Hayhoe *et al*. 2010: 104).Road maintenance costs vary widely, depending upon the season, local context, and future climate scenarios. In Hamilton, New Zealand, changes in rainfall were projected to increase repair costs in spring and winter, but reduced rainfall in spring and autumn partly balanced out the cost; results depend upon the scenario and further investigation was recommended (Jollands et al. 2007).

Informal settlements frequently lack all weather roads and paths within the settlement and connection to the wider road system for emergency vehicle access and rapid evacuation. For instance, informal settlements in Chittagong have extremely narrow roads so that "ambulance and fire services cannot enter most of these neighbourhoods, thus exacerbating the existing health and fire risks at household level" (Rahman et al.,2010: 572). Roads in Lagos's informal settlements are often poorly maintained and lack all-weather surfaces; a 2006 resident survey ranked roads second to drainage in terms of needed facilities (Adelekan 2010). Evacuations in low-income areas may be hampered by hazardous locations, poor quality roads, absence of public transport, prevailing insecurity, and inadequate governance. Following the 2003 and 2006 floods in Santa Fe, Argentina, the lack of information and official evacuation mechanisms prevented a timely response while some low-income residents chose to stay in their homes to protect these and their possessions from looters (Hardoy and Pandiella 2009).

Low-income urban residents can also be profoundly affected by transport disruptions during and after extreme weather events that damage critical public transit links, prevent access to work, and heighten exposure to health risks. Interviews in Georgetown, Guyana, found that low-income households mainly rely on public transport and their limited transport access during floods made them more likely to lose time from work or school, as compared to wealthier households (Linnekamp et al. 2011). Better-off households were more likely to possess their own vehicles, while poorer households rarely owned cars, waded through floodwaters in bare feet, and were thereby exposed to waterborne pathogens (*ibid*.). Some studies suggest that urban women are more likely than men to walk or utilise public transport (World Bank 2010d), so that the gendered impacts of transport disruptions may merit greater consideration (see also UN Habitat 2011a, Levy 2013).

Adapting surface and underground railways: Underground transport systems are specific to urban areas and may have "particular vulnerabilities related to extreme events, with uniquely fashioned adaptation responses" (Hunt and Watkiss 2011: 14). Heat impacts are often significant in underground railways, as these systems may be gradually warming due to engine heat, braking systems, and increased passenger loads (Love et al., 2010). To cope with increasing frequency of hot days due to climate change, "substantial investment" in ventilation or cooling may be necessary (ibid.). Some of New York City's subways are located in coastal or river floodplains, and the system's age, fragmented ownership, and current overcapacity may augment the challenge of adaptation (Zimmerman and Faris 2010: 69-70). Pumps have been installed throughout the subway system and these helped to cope with severe floods in August 2007 during the morning commute (ibid.).

Rail systems that have struggled to cope with existing climate variability may need considerable investment to withstand changes in extreme events and higher temperatures (see Baker et al 2010). Railway systems may also be more vulnerable to climate variability and change than the road system, as the latter can more easily redirect traffic during extreme weather events (Lindgren et al. 2009). The costs of delays and lost trips due to extreme weather events were analysed in Boston (Kirshen et al. 2008) and Portland (Chang et al.2010) and were found to be small relative to the damages upon infrastructure and other property. Portland's nuisance flooding is projected to increase although floodplain restoration, use of porous pavements, or detention ponds may help address this (ibid).

In flood-prone cities, more stringent construction standards, design parameters, or relocation may be needed to adapt transport systems. Much of central Mumbai is built on landfill (as the area was originally seven islands); the landfill areas are prone to flooding, but they contain the main train stations and train lines as well as large populations and a large part of the city's economy (de Sherbinin et al. 2007). Rising sea levels may cause shifts at the sub-surface level of landfill areas and structural instabilities (ibid).

Telecommunications:8.2.2.2 noted how key elements in cities' communications systems may be at risk from climate change impacts so they may need to be strengthened to avoid toppling due to strong winds and electrical support facilities may need to be moved or protected against flooding (see Zimmerman and Faris 2010: 74).

8.3.3.7. Green Infrastructure and Ecosystem Services within Urban Adaptation

The greater attention to understanding, utilizing and protecting ecosystem services includes examples of ecosystem-based adaptation in urban and peri-urban areas. These use opportunities for the management, conservation and restoration of ecosystems to provide needed services and increase resilience to climate extremes. They can also deliver multiple development co-benefits (e.g. purifying water, absorbing runoff for flood control, cleansing air, moderating temperature, preventing coastal erosion) while helping contribute to food security and carbon sequestration (Newman 2010, Foster et al 2011, GLA 2011, Roberts et al 2012; see also Wilson et al. 2011, Oliveira, Andrade and Vaz 2011, Tallis et al 2011, City of New York 2011, Helsinki Region Environmental Services Authority 2012, Institute for Sustainable Communities, undated). An ecosystem services based approach is particularly important in low- and many middle-income countries where livelihoods for sections of the urban population and much of the peri-urban population depend on natural resources. Box 8-1 describes how ecosystem based adaptation is being developed in Durban. Another example is the contribution of catchment management to addressing flood risk that includes community-based partnerships supported by full cost accounting and payment for ecosystem services – rather than the more conventional canalisation of rivers (Kithiia and Lyth 2011, Roberts et al. 2012).

_____ START BOX 8-1 HERE _____

Box 8-1. Ecosystem-based Adaptation in Durban

In Durban, ecosystem based adaptation is part of its climate change adaptation strategy. This seeks to move beyond a focus on street trees and parks to a more detailed understanding of the ecology of indigenous ecosystems. From this can be identified the ways in which biodiversity and ecosystem services can help reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change. Strategies to achieve biodiversity goals such as developing corridors to facilitate species migration, enlarging core conservation areas and identifying areas for improved matrix management to enhance ecological viability of these core areas can have adaptation co-benefits. There is also a recognition that the adaptation deficit is both in the lack of conventional infrastructure and the loss of ecological infrastructure (wetlands, forests, grasslands, soil). It includes an interest in how ecosystem restoration and conservation can contribute to food security, urban development, water purification, waste water treatment climate change adaptation and mitigation.

The development of ecosystem based adaptation in Durban requires a series of steps that include:

1) A better understanding of the impacts of climate change on local biodiversity and how to manage Durban's open space system of 75,000 hectares. The projected warmer and wetter conditions seem to favour invasive and woody plant species.
2) A local research capacity that includes generating needed local data
3) Reducing the vulnerability of indigenous ecosystems as a short term precautionary measure
4) Enhancing protected areas already owned by local government and developing land-use management interventions and agreements with landowners to protect privately-owned land areas critical to biodiversity and ecosystem services. This needs government incentives and regulation to stop development on environmentally sensitive properties, the removal of perverse incentives and support for landowners affected by this.
5) The promotion of local initiatives that contribute jobs, promote business and life skills development and environmental education with ecosystem management and restoration programmes. Durban has initiated a large scale Community Reforestation Programme where community level 'tree-preneurs' produce indigenous seedlings and are involved in the planting and managing of the restored forest areas. This is part of a larger strategy to enhance biodiversity refuges and water quality, river flow regulation, flood

mitigation, sediment control and improved visual amenity. Local level advantages include employment creation and improved food security and educational opportunities.

Source: Roberts et al. (2012).

_____ END BOX 8-1 HERE _____

"Green infrastructure" refers to interventions that seek to preserve the functionality of existing green landscapes (including parks, forests, wetlands or green belts) as well as transforming the built environment through the use of photo-remediation and water-management techniques and by introducing productive landscapes (La Greca et al. 2011, Zhang et al 2011, Foster et al 2011). Its importance for adaptation is increasingly recognized, although much of the early innovation was in response to the need for cost effective and sustainable mechanisms to addresswater shortages or flooding and not directly linked to climate change adaptation. Case studies of green infrastructure aim to measure their effectiveness and assess the potential of urban planning and environmental conservation policies to create cityscapes that can adapt to a changing climate.

Green spaces in cities are considered beneficial for absorbing rainfall and moderating high temperatures. For instance, in the USA, the cities of Portland and Philadelphia have used green infrastructure (including encouragement of green roofs, porous pavements and disconnection of downspouts) to reduce storm waters at much lower costs than increasing storm water capacity (Foster et al 2011).Some cities have made investments in green infrastructure, linked both to regeneration and to climate change adaptation. For instance, the Green Grid for East London seeks to create "a network of interlinked, multi-purpose open spaces" to support the wider regeneration of the sub-region. It is being developed to enhance the potential of existing and new green spaces to connect people and places, absorb and store water, cool the vicinity, and provide a diverse mosaic of habitats for wildlife (GLA 2008:80). New York has a well-established programme to protect and enhance its water supply through watershed protection. This includes city ownership of land that allows crucial natural areas to remain undeveloped and work with land owners and communities to balance protecting drinking water quality with facilitating local economic development and improving waste water treatment. To this has been added an ambitious green infrastructure plan (that includes porous pavements and streets, green and blue roofs and other measures to control stormwater (New York 2010). The city government suggests that while the Program is costly, compared to the costs of constructing and operating a filtration plant, as well as the environmental impacts of the additional energy and chemicals required by filtration, it is the most cost-effective choice for New York (Foster et al 2011, New York 2010).

The coastal city of QuyNhon in Vietnam is seeking to reduce flood risks by restoring a 150 hectare zone of mangroves (Brown et al. 2012). Singapore has used several anticipatory plans and projects to enhance green infrastructure including its Streetscape Greenery Master Plan, constructed wetlands or drains and community gardens (Newman 2010). Authorities in England and the Netherlands are recognising the linkages between spatial planning and biodiversity, though "there is less evidence of direct response to the needs of climate change adaptation" (Wilson and Piper 2008: 143). Barriers to action included short-term planning horizons, uncertainty of climate change impacts, and problems of creating habitats due to inadequate resources, ecological challenges, or limited authority and data (ibid.,145).

In Mombasa, the Bamburi Cement Company rehabilitated 220 hectares of quarry land now known as Haller Park (Kithiia and Lyth 2011). The park attracts over 150,000 visitors per year, with "the potential to create adaptation co-benefits despite this not being the original intent" (ibid.,260). Cape Town has initiated community partnerships to conserve biodiversity, including the Cape Flats Nature project with the para-statal South African National Biodiversity Institute (Ernstson *et al*. 2010: 539). The participating schools and local organisations explore ecosystem services (such as flood mitigation and wetland restoration), and the project facilitates "champion forums" to support conservation efforts *(ibid.)*.

Dedicated green areas within urban environments compete for space with other city-based needs and developer priorities. The role of strategic urban planning in mediating among competing demands for land use is highlighted as potentially useful for the governance of adaptation as presented in planning forerunnersLondon, Toronto, and Rotterdam (Mees and Driessen 2011). The experience in Durban discussed in Box 8-1 also faces many challenges

(Roberts et al. 2012). These include an assumption that ecosystem based adaptation is an easy answer to the technological, financial, institutional and skill constraints that limit the implementation and effectiveness of "hard engineering" solutions (ibid., Kithiia and Lyth, 2011). Experience in Durban shows that implementing an ecologically functional and well-managed, diverse network of bio-infrastructure needs knowledge, new data collection, expertise and resources. It needs to have direct and immediate developmental co-benefits for local communities and ensure integration across institutional and political boundaries. Substantial knowledge gaps need to be addressed, such as the need to determine where the limits or thresholds lie; many ecosystems have been degraded to the point where their capacity to provide useful services may be drastically reduced(TEEB 2010).

Burley et al's (2011) review of the wetlands of South East Queensland, Australia indicates that adaptations focused on wetland and biodiversity conservation may impact urban form in coastal areas. A study of the change in tree species composition, diversity and distribution across old and newly established urban parks in Bangalore, India aims to find ways to increase ecological benefits from these biodiversity hotspots (Nagendra and Gopal 2011).A new methodology that seeks to evaluate the impacts on local climate of current land uses and proposed planning policies using evapotranspiration and land surface emissivity as indicators when applied in Leipzig found that green areas and water surfaces had cooling effects, as expected but some policies were found to increase local temperatures (Schwarz et al 2011).

It is generally accepted that mitigating climate change will require a dense urban form to maximize agglomeration economies in more efficient resource use and waste reduction and to reduce land for urban expansion, reliance on motorized transport and building energy use. But adaptation requires an urban form that favours green infrastructure and requires provision of open space for storm water management, species migrationand urban cooling (Hamin and Garrun, 2009, Mees and Driessen 2011). This suggests that there is a "density conundrum" (Hamin and Garrun 2009: 242) in that higher densities can prevent the maintenance of ecologically viable and biodiverse systems and exacerbate the urban heat island which in turn generates the need for more cooling and may increaseenergy use,further escalating the urban heat island effect. But at which point will densities be too high to maintain ecologically viable and biodiverse systems, especially given that urbanization has already compromised the ability of ecosystems to buffer urban development from hazards? This situation will be further exacerbated by new hazards (e.g. floods, fires) to which systems are or will be exposed as the result of climate change (Depietri et al. 2012).

Green and white roofs:Green and white roofs have been introduced in a range of cities, with the potential to create synergies between mitigation and adaptation.Rooftop vegetation helps decrease solar heat gainwhile cooling the air above the building (Gill *et al*. 2007). This improves the energy performance of buildings (Mees and Driessen, 2011, Parizotto and Lamberts 2012) and can reduce cooling demand and often the use of air conditioning with its local contribution to heat gain (Zinzi and Agnoli 2011, Jo et al. 2010) and its implications for greenhouse gas emissions if utilizing electricity from fossil fuelled power stations. Rooftop vegetation can also retain water during storms, reducing storm water run-off (see studies conducted by Palla et al 2011, Schroll et al 2011, Voyde et al. 2010) and promote local biodiversity and food production (adaptation). Studies which measure the thermal and hydrological responses of green roofs have compared the performance of living roofs across different plant cover types, levels of soil water, and climatic conditions (see e. g. Jim 2011, Simmons et al. 2008). Hodo-Abalo et al. (2012) confirmed that a dense foliage green roof has a greater cooling effect on buildings in Togolese hot-humid climate conditions. Several field experiments combined with simulated modelling of impacts in the US also confirmed the positive thermal behaviour of green roofs when compared to alternative roof coverings (for example Getter et al. (2011) compared green roofs with a traditional gravel inverted roof, Scherba et al. (2011) compared the heat flux into the urban environment of vegetated roofs, white roofs and black membrane roofs, with PV panels elevated above various roofs, Susca et al. (2010) compared black, green and white roofs, in four areas of New York City and assessed the positive effects of vegetation at both urban and building level.

Durban has a pilot green roof project on a municipal building; indigenous plants are also being identified for the project and rooftop food production is being investigated (Roberts 2010). New York's lack of space for street-level planting helped encourage the adoption of living roofs, which can provide additional area for cooling vegetation (Corburn 2009). Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives (Newman 2010).

Based on field tests in the UK, Castleton et al. (2010) suggests that older buildings with poor existing insulation stand to benefit most from green roofs compared to newer structures built to higher insulation standards. Wilkinson and Reed (2009) suggest that the physical property of buildings in city centres causes significant overshadowing, which may mean lower potential for green roof retrofits when compared to installations in suburban areas and smaller towns with lower rise buildings. Benvenuti et al. (2010) highlight the availability of water as the most limiting factor in the realisation of green roofs.

However, a recent meta-analysis suggests that green roofs and parks may have limited effects on cooling (Bowler *et al*. 2010). Findings on green roofs were "mixed, with some evidence of lower air temperatures above green sections in some studies, but not in others" (ibid., 153). Additionally, an urban park was found to be "around 1◦C cooler than a non-green site" (ibid.) and larger parks had a greater cooling effect. Yet studies were mainly observational, lacking rigorous experimental designs, and "it is not clear if there is a minimum size threshold or if there is a simple linear relationship" between the park's size and cooling impact (ibid.). While different types of vegetation have stronger effects, the analysis could not demonstrate "exactly how green infrastructure should be designed in terms of the abundance, type, and distribution of greening" *(ibid)*

Cool roofs or white reflective roofs use bright surfaces to reflect short-wave solar radiation, which lowers the surface temperature of buildings compared to conventional (black) roofs with bituminous membrane (Saber et al 2012). There is also some work on roads and pavements with increased reflectivity (Foster et al 2011). Quantification of the cooling benefits from white roofs in various urban settings has been undertaken - for instance the study in Hyderabad (Xu et al. 2012), comparison of white and black roofs in the North American climate (Saber et al. 2012) and a Sicilian case study (Romeo and Xinzi 2011). Comparisons between green and white roofs have been undertaken in various climatic zones: Ismail et al. (2011) investigated their cooling potential on a single-storey building in Malaysia and Zinzi and Agnoli (2011) explored the comparative applicability of the two roof treatments in a Mediterranean climate. Results suggest that local conditions play a dominant role in determining which treatment is best for improving internal conditions as well as moderating the urban heat-island phenomenon. For instance, Hamdan et al. (2011) found a layer of clay on top of the roof as the most efficient for passive cooling purposes in the Jordanian climate, compared to two different types of reflective roofs.

8.3.3.8. Adapting Public Services and Other Public Responses

It will fall to the public services network and public policy to ensure that climate change adaptation addresses the needs of those most at risk and most vulnerable. Many aspects of this have already been covered – for instance ensuring adequate provision for water, sanitation, drainage and solid waste collection and provision for rapid response to disasters. Health care services and emergency services (including ambulance, police and fire fighting) will have their workload increased while also needing to ensure that their systems can themselves adapt. They also need good working relationships with other key government sectors and with civil protection services – including the armed forces and Red Cross and Red Crescent societies.

As city risk and vulnerability assessments become more common and detailed, these provide a basis for assessing how public policies and services need to adapt – for instance, the levels of risk exposure of key health care facilities from flooding. Availability of data on and the personnel to reach vulnerable urban populations with effective responses e.g. protecting groups particularly vulnerable to heat waves which will be challenging in many cities. There is little evidence of consideration being given to needed changes in public services in response to climate change e.g. the risk of fires is likely to increase in and around many urban centres because of increased drought and rising temperatures.

Enhanced emergency medical services may help cope with extreme events while health officials can also improve surveillance, forecast the health risks and benefits of adaptation strategies, and support public education campaigns. Public health systems may need to increase attention to disease vector control (e.g. screening windows, eliminating breeding grounds for the mosquitoes that are vectors for malaria and dengue) and bolster food hygiene measures linking to increased flooding and temperatures.

The costs of adapting health care systems may be considerable – for instance, where needed modifying buildings and equipment at all levels and training staff and, setting up comprehensive surveillance and monitoring systemsand the use of modelling software that can capture the health risks of Climate Change. Risk and vulnerability assessments also need to look at the complete range of schools and day-care centres to assess their vulnerability to climate change. School buildings can be designed and built to serve as safe centres during floods or storms to which those at risk can move temporarily – although it is also important after a disaster to quickly re-establish functioning schools both for the benefits for children and for their parents (Bartlett 2008).

For cities without a robust emergency response network, adapting to Climate Change may require significant improvements in staffing, resources, and preparedness plans. This will include particular attention to providing emergency services in informal settlements lacking adequate roads or infrastructure and where needed, temporary evacuation plans that serve all those that have to move.

Many sections of 8.2 noted health impacts that can arise or be exacerbated by climate change that will increase demands on health care systems – including those linked to air pollution, extreme weather, food or water contamination and climate sensitive disease vectors. For air quality, additional research is still needed to understand the complex links between weather and pollutants in the context of climate change (Harlan and Ruddell 2011). Important synergies can be achieved through combining mitigation and adaptation strategies to improve air quality, reduce private transport and promote healthier lifestyles (*ibid.*,also Bloomberg and Aggarwala 2008).

8.4. Putting Urban Adaptation in Place: Governance, Planning, and Management

This section discusses what we have learnt about introducing adaptation strategies into the core of urban government investment and management with a buy-in from key sectors and departments within local government and support from non-state actors. This includes experiences with integrating development, disaster risk reduction and climate change adaptation. It includes consideration of household and community based adaptation and of where local processes are or can be supported by higher levels of government and for low- and middle-income nations, by international agencies. It also includes a review of the resources needed to adapt to climate change at urban levels, ranging from human to financial resources.

A share of what is needed for effective urban adaptation falls within the responsibilities of municipal governments. Many aspects of adaptation can only be implemented at the urban level through what local governments do, encourage, allow, support and control. This requires support from regional (sub-national) and national institutions and policies, suggesting that urban adaptation will necessarily be nested and policy-centric, with overlapping responsibilities and authority operating across levels of governance, relevant sectors and themes (Ostrom 2009, Dietz et al., 2003; Blanco et al., 2011; Corfee-Morlot et al. 2011; McCarney et al., 2011; Kehew et al. 2013, forthcoming). There are important precedents here in the way that new national legislation and institutions on disaster risk reduction have helped to strengthen and support local government capacity (see 8.3.2.2), though these often show that without associated budgetary support and increases in human resources, legislation has limited effect on local planning and practice (Johnson, 2011).

Approaches to adaptation include new urban policies and incentives for action as well as measures to mainstream climate considerations or auditing for climate impacts through existing policies to ensure that they reduce risk and vulnerability (Urwin and Jordan 2008, Brugmann 2012, OECD 2008, Satterthwaite et al. 2009). This can include consideration of transformation (where development is a main determinant of risk or risk mitigation), as well as difficult decisions over what can be done where there are limits to adaptation (Pelling and Navarrete, 2011). These limits might include, for example, resettlement or abandonment of previously developed land (see Section 8.3). Capacity constraints, including limited funding and technical expertise, ill-designed or inadequate institutional mechanisms, limited information on climate predictions and risk and lack of leadership will limit the ability of local authorities to work effectively on this (see Gupta et al., 2010) as well as working with others at the local, regional and national level on adaptation. Many national governments face comparable capacity constraints and still do not recognize the importance of local governments in climate change adaptation (OECD 2010a).

8.4.1. Urban Governance and Enabling Frameworks, Conditions, and Tools for Learning

Enabling conditions and frameworks to support urban adaptation are grounded in local-national institutional structures and local competences and interests. Key dimensions of adaptation include awareness, analytical capacity (e.g. assessments of vulnerability and policy options) and action (Moser and Luers 2008). Each presents a different set of challenges and requires specific types of capacity and enabling conditions at city and municipal levels.

As stressed in 8.1, the context for adaptation decisions will inevitably vary by country and location but preconditions for sound urban decision-making and accumulated resilience can be generalised from the literature and experience to date. These relate to principles of good urban government (what government does) and governance (how they work with other institutions and actors including the private sector and civil society). These generally include science-policy deliberative practice and vulnerability assessment to support adaptation (Adger et al. 2009, NRC 2007, 2008, 2009, Renn 2008, Moser 2009, Kehew 2009, Corfee-Morlot et al. 2011). Civil society - including non-governmental and community-based organizations - has important roles in good urban governance and environmental management including community risk assessment and contribution to adaptation, incorporation of local knowledge and understanding local preferences and norms (e.g. Krishnamurthy et al. 2011, Fazey et al. 2010, Shaw et al. 2009, Tompkins et al. 2008, Van Aalst et al. 2008). It is important to recognize that human behaviour and social norms are not static and can evolve through dialogue and understanding (Moser 2006, Dietz et al.2003, Ostrom 2009), hence engagement with stakeholders over time is key to effective adaptation (Kehew et al. 2013 forthcoming). Furthermore, the capacity to act at urban levels varies with organisational form including the level of decentralisation for funding and decisions such as land use and infrastructure (Blanco et al. 2011; Corfee-Morlot et al. 2011; McCarney et al. 2011), which in turn may relate to the context for development (Bicknell et al. 2009).

Section 8.3 made clear how building local adaptation capacity also means enabling disaster risk reduction to limit vulnerability to current and future hazards such as floods, water shortage or heatwaves (e.g. Schipper and Pelling 2006, UNISDR 2008). It includes the capacity to address the physical drivers of vulnerability, such as through upgrading informal settlements and implementing appropriate infrastructure standards and zoning laws, urban planning and early warning systems as well as through better education or information provision (Adger et al. 2007, 2009). The high vulnerability of often-large numbers of the urban poor to extreme weather events and their limited adaptive capacity makes the design and implementation of anticipatory adaptation action, including disaster risk management a key function of urban policy.

8.4.1.1. Multi-Level Governance and the Unique Role of Urban Governments

A framework for urban governance emerges from the challenges climate change brings to multilevel risk governance. Figure 8-1 summarises the key interests and their relationships in the production of urban adaptation governance. In this framework, urban governments (operating at municipal and/or local levels) are provided with authority for relevant policy decisions (Blanco et al., 2011; Corfee-Morlot et al. 2011; McCarney et al., 2011; Kehew et al. 2013, forthcoming). This is combined with the mandates and capacities of quasi-governmental institutions including local water authorities or insurance regulators (in the “inner circle”). Quasi- governmental organisations may operate at a regional scale but include responsibility for urban areas within their remit. Other local stakeholders are ideally included, such as businesses, communities and expert advisors in adaptation decisions, referred to here as part of the “outer circle”. Media and other forms of civil-social infrastructure act as filters of substantive knowledge and help to join expert information with local knowledge to build understanding and engagement on climate change (Carvalho and Burgess 2005; Leiserowitz 2006). Good practice hinges in part upon the credibility, legitimacy and salience of science-policy processes, a strong local evidence base of historical and projected data on climate change, and ongoing, open processes to support dialogue between government, civil society and expert advisors (Cash 2001, Cash et al. 2006, NRC 2007, Preston et al. 2011; Kehew 2013; see also Ch.2). Communication efforts are also essential (Moser and Dilling 2006, Moser and Luers 2008, Moser 2006). Good governance depends in part on how well policy and decision processes mediate across these different actors, spheres of influence, sources of information and resources to co-produce knowledge, support learning and action over time (see Figure 8-1).

[INSERT FIGURE 8-1 HERE
Figure 8-1: Circulation of power for public decisionmaking on climate change.]

From an institutional and policy perspective, urban governments have authority in relevant domains for adaptation decisions but many of their decisions will be enabled, bounded or constrained by national, sub-national or supra-national laws and policies, land use and infrastructure planning decisions (ARUP/ C40 report; OECD 2010; Kehew et al. 2013). Large metropolitan areas raise the level of complexity of managing climate adaptation, especially when they are growing rapidly – and this requires action to be coordinated across multiple urban jurisdictions; the number of relevant jurisdictions varies by city but they are often in the dozens (e.g. Mexico City, Sao Paulo, London and Buenos Aires) and occasionally in the hundreds (e.g. Abidjan and Tokyo) (McCarney et al. 2011). Although there is some evidence of innovative responses at the sub-national levels to plan for extreme weather events and climate change, limited capacity and experience at the local government level also suggests a need for support from higher levels of government (Norman and Nakanishi 2011, Guran et al 2012). In large metropolitan areas, it will also be ineffective for a single urban jurisdiction to act in isolation of neighbouring jurisdictions; there is a need to coordinate and harmonise actions across metropolitan jurisdictions – for instance to implement flood protection of contiguous land areas or evacuation planning in response to an approaching storm or in the event of a disaster.

Adaptive capacity in cities therefore depends upon the alignment of policies and incentives such that they work coherently across multiple levels of government and on multilevel governance to define and deliver effective urban adaptation (McCarney et al. 2011; Corfee-Morlot et al. 2011, Mukheibir and Ziervogel 2007, Urwin and Jordan 2008, Cash et al. 2006, Young 2002, Bulkeley and Kern 2006, Kern and Gotelind 2009). Institutions operating at different levels and with different scopes of authority may be responsible for key decisions in relevant urban adaptation sectors (e.g. coastal zone management and buildings). Water authorities may operate at waterbasin level and as such represent both national and local interests while also operating independently of urban authorities. This points to a need to audit and align (pre)existing policies and screen new policies across levels of government to ensure the consistent integration of urban climate change risk management. Failing to do so can lock-in outcomes that raise the vulnerability of urban populations, infrastructure and natural systems to climate change (mal-adaptation) even where pro-active adaptation policies exist (Benzie et al. 2011; OECD 2009, Urwin, Jordan 2008). Raising urban adaptive capacity requires local government capacity as well as the institutions that facilitate coordination across multiple, nested and poly-centric authorities in making decisions to address urban vulnerability and risk, and which have potential to mainstream adaptation measures.

Opportunities for accelerating learning and action may stem from horizontal coordination and networking across actors, professions and institutions in different municipalities and metropolitan areas, many of whom are facing similar challenges (Lowe et al., 2009, Aall et al., 2007, Schroeder and Bulkeley 2008). Local contexts and implementation agendas also underscore the need for tailoring of national goals and policies to local circumstances and preferences. Consultation and awareness raising are essential to avoid the kind of public backlash that occurred in response to the French government's attempt to ban urban development and require strategic retreat in areas of current and increasing risk to coastal flooding following the storm Xynthia in 2010 (Laurent 2010; Pryzyluski and Hallegatte, 2012). Urban adaptation planning has also to recognise the influence of vested interests and trade-offs, where near-term development may appear to conflict with longer-term adaptation and resilience goals. Public engagement, openness and transparency about climate change information and its risks can help to ensure democratic debate to balance public interests and longer-term sustainability goals against the short-term benefits of unconstrained development.

Urban governments are uniquely situated to understand local contexts, raise local awareness, respond to citizens and civil society pressures, strengthen planning and build capacity to take actions in some areas. They can work closely with local stakeholders through an analytic-deliberative process to build a policy space (Brunner 1996, Brunner et al. 2005, Cash and Moser 2000, Grindle and Thomas 1991, Healy 1997). Within this, it is possible to generate a good understanding of local contextual factors that will matter to decisions about how to manage climate change adaptation (Healy 1997, Ostrom 2009). Urban governments can also promote understanding of climate change risk and drivers of vulnerability for adaptation and help to create a common vision for the future (Corfee-Morlot et al. 2011, Moser 2006, Moser and Dilling 2006, Ostrom 2009). The fact that preferences of different actors tend to be

more homogenous across smaller than larger units (Ostrom 2009) provides opportunities for leadership and flexibility to innovate that may not exist at higher levels of governance. Thus, some evidence suggests that urban governments may be unique in their ability to provide accountableleadership, to innovate and to promote learning-by-doing (OECD 2010).

Beyond setting out a vision for the future, urban governments are central to the interface between climate change and development, including provision for essential services (water, sanitation, drainage, solid waste management, shelter, mobility services as well as education and health services) (Bulkeley 2010; Bulkeley and Kern 2006). Urban governments often have responsibilities for a substantial share of urban infrastructure to provide these services (ARUP/C40 2012). An essential step is to integrate and mainstream adaptation plans and risk management into urban and development planning from local to national levels with a clear time frame, mandate and resources for implementation (Brugmann 2012, OECD 2008, Satterthwaite et al. 2009). This includes influencing territorial development planning and infrastructure planning even if functional authority is at the national or sub-national regional levels (Vigue and Hallegatte 2012, Hall et al. 2012).

Despite the unique opportunities to support adaptation, local government decisions are often driven by short-term priorities of economic growth and competitiveness (Carmin and Dodman 2012, Moser and Luers 2008). Addressing climate change requires shifting ways of thinking about the future to take a longer-term perspective and reconcile this with near-term priorities (Leichencko 2011, Pelling 2011a, Romero-Lankao and Quin 2011). Tension also exists between focusing on economic growth and the large and often growing numbers of the urban poor that are ill-served or unserved by infrastructure and services; for much of the urban population, resilience to climate change will depend on this being addressed (Bicknell et al. 2009). The challenges of advancing adaptation through urban governance processes in low- and middle-income countries are exacerbated by inattention from international donors to urban policy and development concerns, as they work almost uniquely with national governments. Donors may also have preferences for physical infrastructure projects with visible results over local institution and capacity building investments. Similarly, national governments in high-income countries have yet to fully embrace and find ways to support local adaptation initiatives (McCarney et al. 2011).

While there is evidence of growing awareness and analytical capacity (i.e. in the form of adaptation planning) within many urban governments and governance processes, there is much less evidence of action in the form of adaptation implementation and influence on key sectors (Roberts 2010). This may be because adaptation planning is often done separately from urban and territorial development planning making it difficult to gauge progress in efforts to mainstream adaptation into urban planning.

8.4.1.2. Mainstreaming Adaptation into Municipal Planning

Whether and how urban governments mainstream climate change into municipal planning and land-use management and legal and regulatory frameworks for development is key to successful adaptation in all countries (Lowe *et al,* 2009: 6; Kehew et al. forthcoming). Mainstreaming has particular importance in countries where much of the vulnerability and risk from climate change comes from inadequate provision of infrastructure and services (Kithiia 2010, Roberts 2008a). Integrating climate change adaptation in urban development could help planners rethink traditional approaches to land use and infrastructure design based on past trends and move towards a new approach of forward looking risk-based design for a range of future climate conditions (Kithiia 2010; Solecki, Leichenko and O'Brien 2011). Important opportunities also exist in high-income countries to use ongoing planning processes to climate-proof infrastructure, spatial form and land use decisions in cities and to build resilience through existing policy channels (Benzie et al. 2011; Blanco et al. 2011; Urwin and Jordan 2008).

Some have argued that adaptation planning should be an integrated, cross-sectoral process (Parry et al. 2007; Sanchez-Rodiguez 2011) yet initiating mainstreaming may best be achieved through encouraging pilot projects and supporting key sectors to take initiatives. Assigning responsibilities and actions to specific departments can make the climate message easier to understand and more transparent (Roberts 2010, UN-Habitat 2011a). Pilot projects ground the imperative of adaptation in practical reality (Roberts 2010, Tyler et al. 2010; Brown et al. 2012). Sectoral approaches and pilot projects can be a pragmatic way to build more comprehensive and cross-sectoral and

approaches. Urban authorities in India can see climate change adaptation as a priority if they see co-benefits between adaptation and measures to address development and environmental health concerns (Sharma and Tomar 2010) (see also section 8.4.3). Local governments may be able to address both adaptation and mitigation using the same policy levers such as building standards, transport infrastructure, and other urban planning tools (Hallegate et al., 2011). Addressing adaptation and mitigation together can also avoid tradeoffs when designing policies and build response capacity by developing institutional links (Swart and Raes, 2007). A further challenge is to develop methods to evaluate emerging adaptation measures in a timely manner (Hedger et al.2008, Preston et al. 2011).

Despite the potential for change, evidence from the literature suggests that opportunities to mainstream climate change into urban planning and development are so far largely missed (Sanchez-Rodriguez, 2009). Challenges include lack of leadership, inadequate information, institutional compartmentalization and fragmentation, and resource constraints (Sanchez-Rodriguez, 2009; Wilson, et al, 2011). It is difficult to introduce an additional layer of climate change planning to already complex (and often fragmented) planning systems (Kithiia 2010, Roberts 2008a). The planning agenda can be already full, which in turn makes it difficult to find institutional space for climate change adaptation (Measham et al. 2010). Climate change policies may also be seen merely as "add-ons to the overall strategies driven by economic and spatial concerns" (Kithiia and Dowling 2010: 474). In all instances, where progress on adaptation planning is observed, local leadership is a central factor (Carmin and Anguelovski 2009, Measham et al. 2010).

8.4.1.3. Delivering Co-Benefits

Co-benefits of adaptation and development for urban contexts include delivering safer, more comfortable and healthier urban environments and reducing the vulnerability of low-income groups to wider concerns of environmental and public health and local development capacity – livelihoods, skills training, leadership capacity (Burch 2010, Clapp et al., 2010, Hallegatte et al., 2011, Kousky and Schneider 2003, Carmin and Anguelovski 2009, Roberts 2010). Co-benefits also extend beyond the urban core where hazard is driven in part by local environmental conditions such as land-use on hill-slopes or in wetlands – and also influenced by what is done in water-basin management and coastal defence regimes.

Co-benefits may be particularly important to highlight and plan around in low and middle income countries, where lack of policy buy-in is associated with limited local capacity to make changes to policy agendas capacity (UN-Habitat 2011a) and where current climate change challenges appear marginal when compared with the deficits in infrastructure and service provision outlined earlier and other socio-economic problems faced by authorities responsible for urban development and security (Kithiia and Dowling 2010, Roberts 2008a).

Development and climate change adaptation are often seen as separate challenges in a sub-national, regional planning context. A review in OECD countries revealed that only Japan and South Korea are championing climate action as an integral part of sub-national development planning, however Finland and Sweden also have innovative sub-national climate policies and action programmes that are incentivised and funded by the central government (OECD 2010, Ch. 8). For most OECD countries, however, the two issues of urban development and adaptation are tackled separately. Policy research argues that successful adaptation has to be rooted within development context of the city or country and harmonised with its development priorities, such as poverty reduction, food security and disaster management (Moser and Luers 2008, Satterthwaite et al. 2009, Lwasa, 2010, Measham et al. 2011).

8.4.1.4. Urban Vulnerability and Risk Assessment Practices: Understanding Science, Socio-Economics, and Policy Interactions

Principles of good practice in public decision-making and urban climate risk governance include an important component of science. This includes policy exchange and deliberation where good adaptation decisions will necessarily be based on credible scientific and expert information to consider future predictions and uncertainty around these (Bourque et al 2009, NRC 2009, Rosenzweig and Solecki 2010; Government of South Africa,2010). Climate science shows that future changes will need to vary in some cases significantly from past trends, so the past

is no longer a sufficient basis for future planning. Understanding climate risks and vulnerabilities at the urban scale demands a continuous re-assessment of the scientific knowledge about local climate conditions and translating this into useable local knowledge. This will depend upon local capacity to access and use climate change information as it becomes available and processes for local stakeholder engagement in science-policy exercises to understand and assess climate change risk and uncertainties in national, regional and local contexts (Hallegatte et al. 2011; Carmin, Dodman and Chu 2013 forthcoming).

Urban climate science refers to the ability to understand past climate conditions, monitor and attribute historical and present climate change to anthropogenic forcings, and project future changes in temperature, sea level and precipitation sufficiently well that urbanites and urban governments can plan for and adapt to these changes (McCarthy et al. 2010). The paths by which climate change alters local climatic conditions and who is exposed to risk and impacted, will vary with local contextual factors such as local physical and socio-economic conditions (e.g. the size of the local population and its distribution across the land; age structure, the quality, thermal characteristics and location of the built environment; and altitude, soil and vegetation conditions, proximity to the sea or river basins of the area). Urban climate science requires the integration of different kinds of detailed information and projections from physical science and socio-economic domains (Hallegatte et al. 2011, McCarthy et al. 2010). Attention to credibility, legitimacy and salience increase the usability of science and other expert knowledge in policy assessments (from local to global) (e.g. NRC 2007, Preston et al. 2011).

On science-policy issues, such as climate adaptation, research demonstrates the key role of boundary organisations to interpret and shape scientific inputs such that they become more useable in a political context (Cash 2001, Jasanoff 1990, Gieryn 1999, Guston 2001, Driessen et al 2010). In urban adaptation planning, local or regional boundary organisations have also been shown to have influence and support policy decisions (Bourque et al 2009, Corfee-Morlot et al. 2011, Horton et al. 2011). Boundary activities designed to support urban decision-making can take a variety of institutional forms (NRC 2009) and receive funding and support from different sources (e.g. national or sub-national public sources, and in some cases private funding) (Corfee-Morlot et al. 2011). In many instances, key boundary functions are carried out by nearby academic or research communities; local scholars in these institutions can also be a source of leadership for urban adaptation efforts (Molnar et al., 2012; Sanchez-Rodriguez 2009; Government of South Africa 2010).

Even where detailed quantitative and technical urban climate vulnerability or risk assessments exist, the influence of these may be limited if the timing is mis-matched with major policy decisions or if decision-makers do not access and use this information. For example, urban master plans or strategic plans with a time horizon of ten or more years into the future have the potential to incorporate climate risks and vulnerabilities, but timely assessments need to be made available to influence such plans. Beyond timeliness, Moser and Tribbia (2006) explore how decision makers access or use scientific information and the sources they rely upon. Resource managers are more likely to rely upon informal sources, such as maps or in-house experts, media and internet, thanon scientific journals. This emphasises the need to work closely with decision makers in the production and communication of scientific information (ibid, Moser 2006, Cash et al. 2003 and 2006). This demonstrates a need for two-way communication between producers and consumers of scientific and expert information early in any urban climate change assessment and adaptation planning process (Carmin et al. 2012, Horton et al. 2011, McCarthy et al. 2010).

8.4.1.5. Assessment Tools: Risk Screening, Vulnerability Mapping, and Urban Integrated Assessment

Assessments of risk and vulnerability to climate change's direct and indirect impacts are often the first step in getting the attention of governments, especially where these are assessed in the context of general development policy objectives (Hallegatte et al. 2011; see also 8.2). Including risk management information in infrastructure design at the planning or early design phase including that associated with climate change, can avoid higher costs of retrofit at a later date (Baker, 2012, Dickson et al. 2012). This can be assisted through a variety of planning and assessment tools including environmental impact assessment, vulnerability mapping and urban integrated assessment as part of public investment planning and as used by community organisations (UN-Habitat 2007). Governments can ensure that up to date climate information is available to the private sector to support adaptation (Agrawala et al. 2011; see also section below).

A wide range of tools have been developed and used to assess the environmental performance of urban areas including environmental impact assessment tools, environmental audits, strategic environmental assessments and local agenda 21s (Haughton 1999) as well as disaster risk assessment and management tools (Baker 2012). These have potential to support adaptation planning, as they provide useful entry points for adaptation and a means for participatory engagement; however in practice they often give little or no consideration to adaptation (Gurran et al 2012). More reliable, specific and downscaled projections of climate change and tools for risk screening and management can help engage not only relevant public sector actors but also the interest of businesses and consumers (AGF 2010a, UNEP-FI 2011).

Local climate change risk assessments, vulnerability and risk mapping can identify vulnerablepopulations and locations at risk and provide a tool for urban adaptation decision makers (Ranger et al 2009, Hallegatte et al. 2010, Livengood and Kunte 2012). One example is the LOCATE methodology (Local Options for Communities to Adapt and Technologies to Enhance Capacity) that is being tested in eight African countries; in each, a non-governmental organisation is working with one or more communities on project design and implementation, as well as monitoring, evaluation and learning phases. It integrates hazard and vulnerability mapping to inform choices about which populations, infrastructure and areas to prioritise for action (Annecke 2010). Elsewhere, Halsnaes and Traerup (2009) recommend the use of a limited set of indicators, engagement with representatives of local development policy objectives, and a stepwise approach to address climate change impacts, development linkages, and the economic, social and environmental dimensions. There is also a need for assessment tools that go beyond spatial and multi-criteria assessment in order to consider the urban environment as a system; this will allow better understanding of the inter-connections between root causes and risk production, cascading impacts and vulnerabilities (da Silva et al, 2012, UN-ISDR, 2011).

Tools that organize and rank information on vulnerability in different locations often aim to identify relative and absolute differences in risk and resilience capacity (Manuel-Navarrete et al. 2011, Hahna et al. 2009, Posey 2009, Milman and Short 2008). A review of risk screening and assessment tools, and of experience with their use by different donors and their partner countries (Hammil and Tanner 2011) show how these vary from a quick screening to identify risks to a fuller risk analysis and evaluation of adaptation options. In another review, Preston et al. (2011) consider 45 vulnerability mapping studies highlighting two broad functions: problem orientation (i.e. assessing and understanding the problem) and decision support. Noting the wide variety of functions and methods in the mapping exercises, the review suggests that effectiveness is guided by: identifying clear goals; framing vulnerability in a way that is meaningful to users; choice of robust technical methods; and ensuring engagement of the appropriate stakeholder (user) communities.

Downscaling of climate scenarios, systems models and urban integrated assessment modelling at local scales integrate different types of information in a forward-looking framework to support policy assessment in an urban context (e.g. Dawson et al. 2009, Hall et al. 2010, Hallegatte et al. 2011, Van Vuuren 2007, Viguie and Hallegatte 2012, Walsh et al., 2011). Integrated assessment modelling considers the driving forces of urban vulnerability and climate change impacts alongside possible policy responses and their outcomes. By integrating knowledge, this modelling provides a tool for use in urban areas by policy-makers to examine and better understand synergies and trade-offs across policy strategies. From this, policies can be identified that will deliver benefits across multiple criteria (Viguie and Hallegatte 2012, Dawson et al. 2009). These modelling frameworks take time to build and to be integrated into decision maker processes but early results are promising (e.g. Viguie and Hallegatte 2012, Dawson et al. 2009, Walsh et al., 2011).

Despite growing attention, useful information and assessment of climate change at urban spatial scales is generally still lacking (Hunt and Watkiss 2011; Kehew 2009). Only a small number of cities, largely in high-income countries, have quantified risks in local contexts and even fewer have quantified possible costs of climate change risks under different climate, adaptation and/or socio-economic scenarios. Some exceptions exist – as in the case of Durban and the development of a benefit-cost model for climate change adaptation options (Cartwright et al 2013). Other exceptions include urban climate risk assessments carried out in low- or middle-income countries as part of targeted development cooperation programmes and thus supported by external partners (World Bank 2011). Sea level rise and coastal flood risk, health and water resources are among the most studied sectors, while energy, transport and

built infrastructure receive far less attention (ibid, Hunt and Watkiss 2011, Roy et al. 2012). While science and climate change information is increasingly available, socio-economic drivers of vulnerability and impacts, as well as opportunities and barriers to adaptation, are less well studied or understood (Romero-Lankao and Qin 2011; Measham et al. 2011).

8.4.2. Engaging Citizens, Civil Society, the Private Sector, and Other Actors and Partners

8.4.2.1. Engaging Stakeholders in Urban Planning and Building Decision Processes for Learning

If the goal is a resilient, safe and healthy city, having a common understanding or vision of what such a future might comprise at urban scale is a first step to achieving it (Corfee-Morlot et al. 2011, Moser 2006, Moser and Dilling 2006, UN-Habitat 2011a). Participatory processes figure prominently across cities that have demonstrated leadership on urban adaptation (Carmin et al. 2012, Brown et al. 2012, Rosenzweig and Solecki 2010; see also below). This experience is consistent with the conceptual literature that suggests that participatory decision-making is essential where uncertainty and complexity characterise scientific understanding of the policy problem (Funtowicz and Ravetz 1993, Liberatore and Funtowicz 2003). Further, many have argued that, the institutional features of the risk management decision-making process -- notably participatory inclusiveness, equity, awareness raising, deliberation, argument, and persuasion -- will determine the legitimacy and effectiveness of action (Dietz 2003, Corfee-Morlot et al. 2011,Lim et al. 2005, Mukheibir and Ziervogel 2007). Yet a recent review of 45 vulnerability mapping exercises found that only 40 percent included stakeholder participation; this raises questions about procedural justice, legitimacy and salience of contemporary approaches to support adaptation investments and other adaptation decisions (Preston et al. 2011). It also highlights the challenge that local governments face to garner resources, including technical expertise and institutional capacity, to organise and effectively use participatory processes to strengthen rather than delay adaptation decision-making (Carmin, Dodman and Chu, 2013).

In many urban settings, civil society and the private sector already have significant and positive roles in support of adaptation planning and decisions. For example, some studies show that despite limited information, some action is moving ahead on adaptation at urban scale particularly through initial planning and awareness raising (Hunt, Watkiss 2011, Anguelovski, Carmin 2011, Lowe et al 2009, Carmin, Anguelovski 2009). Experience in a handful of cities – e.g. Cape Town, Durban, London, New York -- demonstrate that engaging a wide number and variety of stakeholders at early stages in the risk assessment helps to create political support and momentum for follow-on research and ultimately adaptation planning (Hunt and Watkiss 2011, Anguelovski and Carmin 2011; Rosenzweig and Solecki 2010). In informal settlements where there is little or no formal infrastructure and services, stakeholder engagement provides a means for participatory community risk assessment, where local capacity to adapt is built in part through accessing local knowledge (Livengood and Kunte 2012, Kiunsi 2013). Overtime, it is possible to establish institutional mechanisms that support innovation, collaboration and learning within and across sectors to advance urban adaptation action but this takes time and resources (Mukheibir, Ziervogel 2007, Burch 2010, Anguelovski and Carmin 2011, Roberts 2010).

8.4.2.2. Supporting Household and Community-Based Adaptation

In well governed cities, community groups and municipal governments are mutually supportive providing information, capacity and resources in maintaining local environmental and public safety. Where local government has not yet formulated adaptation strategy, community groups can be important in raising political visibility for climate risks and in providing front-line coping (Wilson, 2006; Granberg and Elander, 2007) including highlighting gender disparities in urban risks (Björnberg and Hansson, 2013). Where cities are less well managed and governed, community organizations may be discouraged and seen as a threat to formal urban planning. They may have to lobby an under-resourced municipality in the hope of getting some provision for infrastructure. Or they may have to address the deficit in roads, drains, good quality buildings and other infrastructure and services themselves (and thus it also falls to them to build local resilience to climate change impacts). This has been observed in rapidly urbanizing middle-income (Redclift, et al 2011) and low-income countries (Pelling, 2011a). But it is generally only in middle

and upper income residential developments that the full range of infrastructure and services needed for resilience can be afforded.

However, in many cities, community organizations formed by lower-income groups offer a rich resource of flexible capacity that can adapt to take on local priorities for development under climate change (Mitlin and Satterthwaite 2013). They are active in coping that better uses current resources to live with risk and at adaptation that seeks to realign resource options to prepare for future risks. But shifting the burden of adaptation to the community level is unlikely to bring success. Work from the Caribbean and Latin America has indicated the necessity of supportive linkages to wide community networks and/or local government for community level adaptation to be sustainable (Pelling 2011b)

Individuals and households in informal settlements are well used to coping with environmental hazards and the human vulnerabilities that generate risk; they have been shown to take multiple measures to mitigate the impact of extreme weather, especially where there is a history of floods, heat waves or high winds (Wamsler 2007, Adelekan 2010, Jabeen et al. 2010, Livengood and Kunte 2012, Kiunsi 2013). Some seek to modify the hazard itself e.g. ventilation and roof covering to reduce high temperatures during heat waves or barriers built to prevent floodwater entering homes) or reduce their exposure e.g. by sleeping and keeping food stores on top of high furniture and moving temporarily to safer locations. Exposure reduction measures are the most common *(*Douglas et al 2008).

There is an important distinction to be made between coping and adapting. SREX (IPCC 2012) distinguishes between coping as acts that bring together existing resources and entitlements to protect against a current threat, and adaptation, which seeks to adjust entitlements and future resource portfolios in the expectation of future risk. Many studies show the importance of coping mechanisms for low-income households because they lack the resources or capacities for adaption. A study in Korail, one of the largest informal settlements in Dhaka, showed that diverse household responses to flood risk (see Figure 8-2 for one example of this). Measures include barriers across door fronts, increasing the height of furniture, making floors or shelves to store goods above the flood line. Provision for ventilation, creepers or other material on roofs and false ceilings helped to keep down temperatures. Households also used portable cookers that can be used on shelves or furniture (Jabeen et al. 2010). These are important coping responses (and comparable responses are found in many informal settlements – see for instance Adelekan 2010 and Kiunsi 2013) but they do not articulate capacity to adapt – to influence future coping.

[INSERT FIGURE 8-2 HERE
Figure 8-2: Household adaptation - a cross section of a shelter in an informal settlement in Dhaka (Korail) showing measures adapting the dwelling to better cope with flooding and high temperatures.]

There are also constraints on the capacity of low-income households to act. For instance, in Korail, many inhabitants did not move to safer locations when floods are anticipated because this risked loss of assets from theft and disrupting livelihoods (Jabeen et al. 2010). They also worried whether they would be allowed to return to their original location. Similar concerns were expressed by the inhabitants of informal settlements during flooding in Santa Fe, Argentina (Hardoy et al. 2011). There is some recognition that strengthening and supporting the asset base of low-income households helps increase their resilience to stresses and shocks, including those related to climate change (Moser and Satterthwaite 2008.).

Community-based adaptation arises when a group of residents in a particular settlement agree to work together to address a perceived risk they face that the city government is not addressing (Boyd et al. 2009, Dodman and Mitlin 2011). These responses to climate change can be autonomous of, or engage with, local governments, sometimes via networks of community organization or with brokerage from NGOs (Mitlin, 2012). There is typically far less need for comprehensive community action in well governed cities, as shown in Table 8-2. In low and most middle-income nations where capacity and resources are most stretched as well as cities in high-income countries with inadequate governance and resource base, enabling community based adaptation and building resilience is more relevant. This is because of the limited capacity of governments to provide much needed risk-reducing infrastructure and services or their unwillingness to work in informal settlements. A range of studies documents how local populations have a depth of knowledge and capacities to mitigate their vulnerabilities (Dodman and Mitlin 2011, Anguelovski and Carmin 2011, Livengood and Kunte 2012). Close to a billion people live in informal settlements in

urban areas across the world and for a high proportion of these, community-based adaptation is their only means of response.

Community-based responses are often reactive – also more coping than adaptation facing - as residents within a particular settlement work together to install or repair infrastructure or provide services or action to engage local government and if possible work with it. There are many precedents for this engagement with local governments, including many upgrading programmes in informal settlements that have improved housing quality and infrastructure provision. Most upgrading programmes also mean that those living in these settlements became incorporated into 'the formal' city and this often means other measures by the state to reduce their risks – for instance though access to schools, health care and safety nets (Almansi 2009, Boonyabancha 2005, Fernandes 2007, Ferguson and Navarrete 2003, Imparato and Ruster 2003, Some et al , 2009, UN Millennium Project 2005). In many informal settlements, the issue of land tenure is difficult to resolve and this impedes upgrading programmes and local level adaptation action (Boonyabancha 2005, 2009, Almansi 2009). Where upgrading is able to deliver basic needs and services including security of tenure this can act as a foundation for coping and potentially adaptive capacity. Where adapting to or coping with climate change dovetails with the meeting of existing priorities and reducing existing risks, considerable local scope can exist. But where climate change or disaster risk are seen as distant or low probability then the immediate pressures of poverty tend to dominate local agendas (Banks et al. 2011). The studies noted above highlight how the willingness of individuals to invest in collective action is influenced by their tenure status. Tenants and those with the least secure tenure are often amongst the most vulnerable and exposed to hazards but also are usually unwilling to invest in improving the housing they live in and less willing to invest in community initiatives. But the contribution of community-level organization, DRR and climate change adaptation can be greatly enhanced where local governments and other agencies like civil defence organizations recognize the potential role of community organization and action and support them.

It has become more common for local governments to work with community-based organizations not only in upgrading but also in disaster risk reduction (Pelling 2011b, United Nations 2009, 2011, IFRC 2010). Community-based adaptation will probably be preceded by community-based actions to reduce risks and vulnerabilities to flooding, storms and heat waves in the past (Archer and Boonyabancha 2011, Carcellar et al 2011). But there are limits to what community action can do in urban areas. For instance it may be able to build and maintain community water sources, toilets and washing facilities or construct or improve drainage (see for instance the large community-driven sewers and drains programmes in cities in Pakistan Hasan 2006) but it cannot provide the network infrastructure on which these depend (e.g. the water, sewer and drainage mains and water treatment) or city-region management (Satterthwaite et al. 2009). Most informal settlements are embedded in a larger built up area so there is no space in their periphery to which to channel flood waters or dispose of household wastes. But here, supportive local governments or utilities can help – for instance in Karachi, the water and sanitation utility supported the community-driven provision mentioned above by providing the trunk infrastructure into which it could integrate. There are also many examples of where community organizations in informal settlements negotiated inclusion into formal water and sanitation systems (Boonyabancha 2005), such as in in Penjaringan, a low-income informal settlement in North Jakarta, where community groups organized to gain connection to the city piped water network (Prabaharyaka and Pooroe 2010).

Urban resilience to climate change impacts requires actions, investments and governance frameworks that only local governments can provide, even though private sector and community-based action may support this. A focus on community-action may mean a lack of attention to the structural and institutional inequalities or failures that underpin local vulnerabilities and the failure of local governments and agencies to address these (Dodman and Mitlin 2011). Table 8-3 illustrates the contemporary limits of community based action across key sites of coping and adaptation – highlighting where strategic partnerships, especially with a supportive municipal government have key advantages.

[INSERT TABLE 8-3 HERE
Table 8-3: The possibilities and limitations of focused activity for community groups on climate change.]

The IFRC (2011) identify three broad requirements for successful urban community based disaster risk reduction, work that can be extended to assess coping and adaptive capacity. These requirements are: (1) the motivation and

partnerships of stakeholders; (2) the levels of community ownership, wider integration and flexibility in project design, and (3) having sufficient time, funding and management capacity.]

The effectiveness of community-based action is also dependent on how representative and inclusive the community leaders and organizations are. There are examples of its effectiveness where there are representative organizations formed by those living in informal settlements (Appadurai 2004, Mitlin 2012) but also examples of local political structures that inhibit this (Banks 2008 and Houtzager and Acharya 2011). There are also wider constraints on the capacity of community organizations to act. For instance, discussions in El Salvador with the inhabitants of 15 disaster-prone "slum" communities and with local organizations showed many making individual and household responses – but difficulties in getting community action as there were no representative community organizations through which to design and implement settlement-measures. In addition, there was a lack of support from government agencies and from civil society organizations (Wamsler 2007).

The effectiveness of community-based adaptation in urban areas depends on the extent to which community organization (and the larger networks or federations they form) can generate pressure for larger changes within government and for relations between community organizations and government (Boonyabancha and Mitlin 2012). Community-based adaptation can engage with key development agendas that reduce poverty and vulnerability (Sabates-Wheeler et al. 2008) and potentially be effective in light of local inequalities and adverse power relations at district, city, national and transnational levels (Mohan and Stokke 2000). But urban governance regimes are often resistant to challenge and civil society organizations can be marginalized or co-opted reducing scope for adaptive action at the level of governance (Pelling and Manuel-Navarrete, 2011)..

There are new methods of documenting and mapping risks and vulnerabilities in informal settlements that serve and support community based adaptation. Even though it is common for a third or more of the inhabitants of cities in low- and middle-income nations to live in informal settlements, these are often not included in official government records and maps. In a growing number of cities, the mapping and enumeration of informal settlements has been undertaken by residents organizations supported by grassroots leaders and local NGOs – with city governments coming to support these and recognizing the validity of the data and maps produced (Patel and Baptist 2012). These provide the household and settlement data and maps needed to plan the installation or upgrading of infrastructure and services that reduce risks from extreme weather. Some of these community-driven enumerations also collect data for each informal settlement on risks and vulnerabilities to extreme weather and other hazards (Pelling 2011b, Carcellar et al. 2011, Livengood and Kunte 2012, UNHABITAT 2007). For instance, community surveys in the Philippines identified at risk communities under bridges, near cliffs and other landslide-prone areas, on coastal shorelines and river banks, in public cemeteries near open dumpsites, and on those in flood-prone locations (Carcellar et al. 2011). This mapping also helps raise awareness among the inhabitants of informal settlements of the risks they face, as well as getting their engagement in planning risk reduction and making early warning systems and when needed emergency evacuation effective (Pelling 2011b).

8.4.2.3. Private Sector Engagement and the Insurance Sector

Cities represent a particular interest for companies because much business activity, private investment and demand is concentrated there and because of their dependence on the functioning of infrastructure and usually a wide range of services. Brugmann (2012) notes how cities concentrate a high proportion of global investment and value added in global supply chains of production, and therefore a high proportion of what requires adaptation (and the funding needed to realize it). He argues that the costs of effective adaptation reaches far beyond what governments or international agencies can provide and depends on catalysing market-based investments in adaptation and financial instruments that reward investors who contribute to resilience. There is also a large number of private service providers and professional associations -- including architects, engineers and urban planners – positioned to influence the pace and quality of adaptation efforts (McBain et al. 2010).

Others argue that most of the investment required for sound adaptation will come from a multitude of private decisions spanning individuals, households and firms (Bowen, Fankhauser et al. 2008, OECD 2008). In contrast, international discussions often assume that the public goods nature of adaptation will require a major public

investment to cover the principal adaptation needs in low- and middle-income countries (AGF 2010b and c). Even when considering this more political set of questions around how to support adaptation efforts internationally, it is clear that the need for adaptation investments will far exceed available funds from public budgets (Hedger 2011, OECD 2008, World Bank 2010e). This underscores the need for both public and private engagement to address adaptation.

For markets to work in favour of urban adaptation, the private sector will need to see financial value in getting involved. In a survey of the most serious risks that companies face (Aon 2011), the top ranked risks were economic slowdown, regulatory/legislative change, increasing competition and damage to reputation. Weather and natural disasters came16th and climate change 44th – even if some risks that were ranked higher may be associated with climate change impacts (business interruption was 5th, commodity price risk 8th and distribution or supply chain failure 12th). It is not clear that private sector actors are well positioned to consider the big questions of urban development that climate change adaptation requires (Redclift et al. 2011). For example, in Cancun, Mexico close relationships between government and the corporate private sector, and the push for lucrative urban development, have led to a failure to reflect on the urban development model and generates climate change risk through hazard exposure of capital intensive and large-scale coastal development. Private sector investments in adaptation in this context are limited to superficial changes, for example in building design to withstand hurricanes; most investment in risk management comes from the state sector through for example beach replenishment and a focus on policies for rapid disaster recovery (Manuel-Navarrete et al. 2011).

The Private Sector Initiative of the UNFCCC Nairobi Work Programme offers support for businesses to integrate climate change science into their business planning, including urban infrastructure and high technology developments (see http://unfccc.int/adaptation/nairobi_work_programme/private_sector_initiative/items/6547.php). This experience has shown that both public and private (including civil society) actors can have a role in providing regional and local climate predictions and hazard mapping e.g. data and projections on socio-economic trends, climate change, urban water supply and management practices and land use and building trends (UNEP-FI, 2011). A recent review of private sector engagement in adaptation shows anecdotal evidence of some large businesses beginning to invest in vulnerability assessments, yet few have begun to invest in adaptation; these include business with assets at risk to climate change, or with dependence on natural resources that are particularly exposed to climate change e.g. freshwater resources (Agrawala et al. 2011). While some private sector actors may be pro-active in taking action against climate change risks, many more will postpone upfront investments for longer-term benefits against uncertain risks. Eakin et al. (2010) and Chu and Schroeder (2010) suggest that the private sector may become more prominent when local governments and civil society action is limited but this raises the issue of what incentives private sector enterprises require to do so and whether they will do so for the public good.

Insurance markets can play a unique role in urban adaptation by sharing and spreading financial risk from climate change, for example, to help limit damages and manage risks of climate change in urban flood prone areas (Rosenzweig and Solecki 2010). Risk-differentiated property insurance premiums can incentivise individuals and businesses to invest in adaption or to avoid being or building in high-risk areas (e.g. flood prone or fire hazard areas) and retro-fit property to reduce risk (Fankhauser et al. 2008, Mills 2007). Relevant insurance instruments include provision of health and life insurance to individuals; property and possessions insurance for home and commercial property owners, and micro insurance or micro finance mechanisms to support those in low-income urban communities that are not covered by commercial insurance (see Box 8-2) Catastrophe bonds may also be developed to cover some urban climate risks, however experience to date suggests that they are written quite narrowly - for specific events in specific locations - and thus may not provide the broad protection necessary to limit catastrophic risk as warranted in a changing climate and urban context (Brugmann 2012, Keogh et al. 2010).

Where risk levels exceed certain thresholds, insurers will abandon coverage or set premiums that cannot be afforded by most of those at risk. Private investment or standard insurance markets will not protect low-income urban dwellers, many of whom live in informal settlements where risk levels are high, where insurance is often inappropriate (few assets are legally owned), inaccessible (they are unable to get bank accounts that are required), or unaffordable (premiums set too high so that the up-front costs of insurance prevent its take up) (Ranger et al., 2009, Hallegatte et al. 2010). For example, around half of Mumbai's population currently live in informal settlements, most of which have inadequate provision of basic infrastructure and are at risk to floods today (Hallegatte et al.

2010, Ranger et al. 2011, McFarlane 2008). The risk profile for this informal settlement population is set to increase under most scenarios of climate change. This population will not be served by insurance mechanisms unless the risks they face are greatly reduced (and thus insurance costs lowered). They will rely instead upon government assistance and local solidarity, such as family and community support, to respond when disaster hits (Hallegatte et al. 2010). So insurance while reducing net risk and loss potential in urban areas can increase inequality in security across the city and within neighbourhoods or across regions (da Silva 2010).

In many informal settlements, informal savings groups are active and provide members with quick access to funds. Most savers and most savings managers are women and these groups have particular importance for providing their members with rapid access to emergency loans (Mitlin 2008). Where access to formal banking is limited by poverty, but where social capital is high, slum dwellers have pooled their savings and used these for collective investments that reduce risk within their existing settlement or reduce risk by allowing them to negotiate land and support where they can build new homes (d'Cruz et al 2013, Manda 2007, Mitlin and Muller 2004).

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Box 8-2. Microfinance for Urban Adaptation

Microfinance schemes may contribute to pro-poor, urban adaptation through a variety of different instruments including micro-credit, micro-insurance and micro-savings to help households and small entreprenuers that do not have access to formal insurance or commercial credit markets. To date, these have been applied mostly in rural areas generally benefitting those with some property status (and thus not the poorest of rural populations). As Hammill et al. (2008: 117) state: "*The value of MFS holds for climate change adaptation is in its outreach to vulnerable populations through a combination of direct and in-direct financial support, and through the long-term nature of its services that help families build assets and coping mechanisms over time, especially through savings and increasingly through micro insurance – products and sharing of knowledge and information to influence behaviours*." Although typically more costly than commercial bank loans, micro-finance can support entrepreneurial undertakings by those unable to get bank loans, help diversify local economies and empower women in particular, which can in turn contribute to adaptive capacity in a local context (World Bank 2010c, Agrawala and Carraro 2010). But micro-finance may focus on short-term gains by encouraging growth in risk-prone areas and sustaining livelihoods with little resilience to climate change (Agrawala and Carraro 2010). This suggests a need for "climate-proofing" microfinance practices and targeting its use to priority tasks that will deliver adaptation and development benefits in the nearer term including disaster risk reduction and community based technical training and education (ibid.). Microfinance also provides a means for donors to deliver support to low-income groups without creating an ongoing dependence on aid (ibid., Hammill et al. 2008). But one limitation of micro-finance for adaptation is that it typically provides credit to individuals for their use only, so it is not easily used to help finance collective investments - for instance to improve drainage - and can be a route into indebtedness especially during disaster recovery. There has been some experience of pooling savings, e.g. in low-income communities to set up City Development Funds in Asia, from which they can draw loans for disaster rehabilitation among other things (Archer 2012).

_____ END BOX 8-2 HERE _____

For the private sector to fulfil its potential to facilitate adaptation, public policy needs to establish enabling conditions in markets (see 8.3). For example, urban policies can target payment for provision of ecosystem services that will otherwise fall outside of the market system to provide adaptation benefits; such services include storm buffering and flood protection through payments for mangrove protection in coastal zones or payment for protection of urban green space along river-ways (Fankhauser et al., 2008, Roberts et al. 2012). In the buildings sector, well-documented examples of market failure exist where optimal investment in weather proofing new construction and retrofitting existing stock will not occur without regulatory intervention; this is also an area where municipal governments often have authority to act. Public policy and funding is also needed to protect the poorest and most vulnerable populations, who are least able to protect themselves through private action. More generally, where information is highly uncertain or not consistent with past experience, as is the case for the prediction of extreme weather events and potential losses, public policy has a role to help provide information about risks and to ensure

action e.g. to fill gaps in insurance markets where insurers are unable or unwilling to act (Fankhauser et al., 2008, Mills 2007, SREX 2012, UN-Habitat 2011). For example, regulations can require pro-active engagement of the private sector, as in the UK, where vulnerability assessment is required for infrastructure investments with implications for urban planning and investments (Agrawala et al., 2011). Other examples exist where urban governments lead by example by requiring the integration of adaptation considerations into public operations and infrastructure investments through procurement requirements, which in turn affects private sector providers of services and products in the supply chain of these operations. Thus even where markets exist and are well-functioning, public intervention – spanning local to national level action - is warranted as a means to engage the private sector in adaptation. There will also be a role for public-private initiatives to provide educational and skill development resources to ensure that professional networks of private service providers (i.e. architects, engineers and urban planners) are trained in the latest decision tools, assessment methods and practices (McBain et al., 2010, da Silva, 2012)

8.4.2.4. Civil Society Partnerships and Philanthropic Engagement

Philanthropic and other civil society support for urban adaptation is gaining rapid momentum at all levels of operation. The most diverse are local actions undertaken by community based organisations, and these often build on long experience of working with the urban poor on livelihoods, governance and basic needs fulfilment. The greatest learning process has taken place amongst international philanthropic and civil society humanitarian organisations that now take urban adaptation seriously and build from experiences in urban climate change mitigation and rural adaptation respectively. These are sectors where lessons are not easily transferred so that new experimentation and practice development is underway.

An expression of international civil society as an enabling framework is the role played by philanthropic organizations.

One example of this is the Rockefeller Foundation's support for the Asian Cities Climate Change Resilience Network (ACCCRN). This is supporting partner institutions in ten cities in India, Indonesia, Thailand and Vietnam to build local knowledge, capacity and strategies to institutionalise climate change adaptation and resilience in local planning and development. This includes prioritising support for interventions to guide future investments to build resilience into the measures to meet the diverse needs of residents, businesses and the urban economy (Moench et al. 2011, Brown et al 2012). Others, such as the Bill and Melinda Gates Foundation approach urban adaptation indirectly through interests in poverty and disaster response and emphasise capacity building through education including programme support for universities in disaster-prone regions in Africa and Asia to establish a network of education and development programs in disaster resilience and leadership organized from Tulane University, New Orleans. The growth in philanthropic foundation spending has as yet largely unresearched implications for the direction of knowledge and capacity building on urban adaptation (Buchner et al. 2011).

Many civil society initiatives have developed models of infrastructure delivery; these are not centered on adaptation but they do have relevance for it. For instance, the installation of community-managed sewers and drains supported by the Orangi Pilot Project Research and Training Institute in urban areas in Pakistan shows capacity at community level but also how the scale and scope of what could be achieved was much increased by supportive investments by government (Hasan 2006). Elsewhere ad-hoc coalitions of civil society actors, or uncoordinated activity in many other cities provide a de facto delivery mechanism for accessing basic infrastructure and rights as part of development and disaster response (Pelling 2003). Here, while individual community groups may be foresightful and adaptive, the lack of coordination across communities limits the scale and scope of adaptive capacity. Adding to the argument for enhanced civil society coordination is the recognition that many disaster events are small, local but have a widespread and cumulative impact on the development prospects of low-income households and communities (United Nations 2009). The scale and range of recent disaster events in Asian cities suggest a growing need for new support mechanisms to facilitate action among local stakeholders – one that should include local government as well as local civil society organisations (Shaw and Izumi 2011). One experiment in this regard, though not exclusively focused on urban contexts, is the Global Network of Civil Society Organizations for disaster risk reduction. This has organised community groups at national and then (supra-national) regional and global levels

in a structured assessment of the local delivery for disaster risk reduction goals, as set out in the Hyogo Framework, as a means of verifying claims made by national government submissions to the ISDR.

Where urban-based civil society is well coordinated and has high degrees of legitimacy, it can reach beyond this to offer alternative models for urban governance and for adapting to climate change as part of the development struggle (Mitlin 2012). These are alternatives that need not be in confrontation with local government. Evidence from Santo Domingo, the Dominican Republic has shown the importance of partnerships between local urban government and local civil society actors in achieving longevity, in options for upscaling local disaster risk reduction initiatives and for building on trust generated by such projects to deliver other gains, in this case improved policing and reduction in gang related violence (Pelling 2011b). In the Philippines, many local governments now work with the Philippines Homeless People's Federation in identifying those most at risk to natural disasters and acting to address this (Carcellar et al., 2011)

The coming together of grassroots civil society organisations to form international collaborations strengthens the framing role of civil society while retaining its local accountability and focus. The local situatedness of adaptation and the need to both address local conditions and structural root causes of vulnerability makes such organisations well placed. Amongst the most active with a dedicated urban focus is Shack/Slum Dwellers International (SDI), a network of community-based organizations and federations of the urban poor in 33 countries in Africa, Asia, and Latin America and their local support NGOs. Its member federations share experiences, lobby and undertake practical upgrading and risk reduction initiatives as well as seeking to influence the policies of development assistance agencies. Regional networks of organisations also contribute to the emerging international architecture of civil society movements working on risk reduction - for example, the Asian Coalition for Community Action Program managed by the Asian Coalition for Housing Rights is supporting community-driven upgrading initiatives in 150 cities in 18 different nations and supporting improved relations between community organizations and local governments (REF). Other civil society networks have broader interests but include urban risk reduction, for example the Asian Disaster Reduction and Response Network (ADRRN), which aims to strengthen local civil society groups in the region.

8.4.2.5. University Partnerships and Research Initiatives

Since AR4, interest in urban aspects of adaptation has grown amongst researchers and universities and some associated national research funding agencies. This is also evident in the number of conferences on this topic and in the number of professional societies (including architects, urban planners and engineers) that are considering their roles and responsibilities. Parallel agendas from social and behavioural sciences and policy on one hand and engineering and city planning sciences on the other are beginning to integrate. Examples of this include the Urban Climate Change Research Network (UCCRN), which brings together researchers and city planners to exchange knowledge and build a coalition of awareness and policy – particularly important when national level policymaking on adaptation is slow (Rosenzweig et al, 2010).

The Urban Global Environmental Change Programme (UGEC) of the International Human Dimensions Programme of the Earth Systems Science Partnership (ESSP) was a pioneer in promoting social science and knowledge exchange and has built international networks in adaptation, mitigation and relationships between these two. Urbanization and adaptation has become a thematic issue dealt with by the Land-Ocean Interface at the Coastal Zone (LOICZ) programme through its interest on megacities and costal urban regions. The role of adaptation and its interaction with disaster risk reduction is also highlighted by the International Scientific Union project, Integrated Research on Disaster Risk (IRDR). There is also the IDRC funded research on urban adaptation in Africa and the START programme supporting research on global environmental change in Africa and Asia-Pacific.

Individual academic institutes have also begun to champion and support urban adaptation efforts. For example the Urban Observatory in Manila has become a regional hub for climate change science and urban adaptation, though interests in mitigation and rural adaptation are much more developed. In Malaysia the Universiti Kebangsaan Malaysia hosts a Malaysian Network for Research on Climate, Environment and Development (MyCLIMATE) and has focused on building awareness and capacity amongst industry and civil society (Izumi and Shaw, 2011). The

Climate and Disaster Resilience Initiative (Kyoto University, CITYNET and UNISDR) has focused on working with city managers and practitioners (Shaw and IEDM Team 2009). Centres for capacity building are also emerging such as the International Centre for Climate Change and Development (ICCCAD) in Dhaka which offers short course on urban adaptation planning (Mehrotra et al. 2009, Anguelovski and Carmin 2011, Molnar et al. 2010). In Latin America networks such as FLACSO provide leadership across the region in disaster risk reduction, management and climate change adaptation. Such networks can bring knowledge across urban centres and connect to international knowledge. Individual centres have also become more engaged in urban adaptation from established expertise in urban climate change mitigation (eg UNAM in Mexico).

8.4.2.6. City Networks and Urban Adaptation Learning Partnerships

The growing interest in urban adaptation among researchers and urban governments is also seen in the growth of transnational networks where urban actors work across organisational boundaries to influence outcomes (Bulkeley and Betsill 2005, Bulkeley and Moser 2007, Rosenzweig et al 2010). Some of these have been created through formalised information networks and coalitions acting both nationally and internationally, including ICLEI's Cities for Climate Protection, the Climate Alliance, the C-40 Large Cities Climate Leadership Group, and the Urban Leaders Adaptation Initiative in the US. The United Cities and Local Governmentsthat represents local governments within the United Nations have a growing interest in climate change adaptation. The Asian Cities Climate Change Resilience Network (ACCCRN) mentioned above also encourages inter-city learning for officials and local researchers (Brown et al. 2012). The Making Cities Resilient network supported by the UN International Strategy for Disaster Risk Reduction seeks to catalyse city governments to take action based on a ten-point priority agenda that includes a call to adapt to climate change by building on good risk reduction practices (UNISDR 2008; see also Johnson and Blackburn 2013).

The role of these networks have received increasing attention in social research on climate policy. For example, ICLEI's Cities for Climate Protection network has been extensively analyzed in the literature (Aall et al. 2007, Betsill and Bulkeley 2004, 2006, Lindseth 2004). The initial focus of some of these networks was on mitigation but attention to adaptation is growing (as in the US Urban Leaders Adaptation Initiative - Foster et al. 2011). These groups have given an institutional foundation to concerted effort and collaboration on climate change at city level (Aall et al. 2007, Kern and Gotelind 2009, Romero Lankao 2007).

8.4.3. Resources for Urban Adaptation and their Management

Resources for urban adaptation action can come from domestic and international public and private sectors. Table 8-4 summarizes the main financial instruments that can help fund adaptation in cities. For high-income countries, estimates show that local governments are responsible for about 70 percent of public spending and roughly 50 percent of the public spending on environment infrastructure – although often operating in partnership with other levels of government (OECD 2010). The scale and source of funds that might contribute to adaptation varies widely by city and location. The local revenue sources available to an urban government depends upon the national institutional and legislative framework that devolves some authority to tax or imposes other fiscal policies on local residents, property owners and businesses. Some of the environmental innovation shown in cities in Latin America over the last 20 years is associated with decentralization that has strengthened fiscal bases for cities, as well as elected mayors and more accountable city governments (Campbell 2003, Cabannes 2004). Much less is known about urban fiscal policies in Africa and Asia except that a high proportion of urban governments have very limited investment capacities as most of their revenues go on salaries and other recurrent expenditures (UCLG 2011).

[INSERT TABLE 8-4 HERE
Table 8-4: Main sources of funding and financial instruments for urban adaptation.]

Table 8-4 highlights how large cities with strong economies and administrative capability are most able to attract external funding (including transfers from higher levels of government) and raise internal funding for adaptation. There are far fewer possibilities for less prosperous and smaller urban centres and for cities with fragmented

governance structures or where administration is manifestly lacking in capability. One key issue here is 'unfunded mandates.' In many nations, local governments have been assigned responsibilities without the needed increase in funding and capacity (UCLG 2011) – and this may now also happen in relation to new responsibilities for adapting to (or mitigating) climate change (Kehew et al. 2012). The implication is that the funding regime and supportive legal frameworks need to integrate climate change risk management and adaptation into development.

8.4.3.1. Domestic Financing: Tapping into National or Sub-national Regional Sources of Funding and Support

Domestic public funding is one of the most significant and sustainable source of funding for adaptation in many countries. In recent years, initiatives to green local fiscal policies have spread. These include congestion charges on automobiles and value-capture land taxes that make visible the cost of environmental externalities and/or the benefits of infrastructure and services provided to property owners (e.g. transport, water and wastewater services). Such measures can promote private investment in risk management while mobilising local revenue sources (where a portion could be targeted to support urban adaptation). Local fiscal incentives for mal-adaptation may also exist, e.g. in China and parts of Québec, urban government budgets and actions are financed by land sales, which in turn promote urban sprawl or development in areas at risk (Merk, 2012; Drejza et al. 2012). Greening local fiscal policies will need to identify and address pre-existing policies that incentivise mal-adaptation.

Another important source of funding for local adaptation is grants, loans or other forms of revenue transfers from national or regional (sub-national) governments (OECD 2010: Ch 9, Hedger and Bird 2011). OECD (2010:239) states: "*In cases where environmental policies with large spillovers are assigned to local governments, intergovernmental grants could make sense in order to compensate local governments for the external benefits of its expenditures*." One example of this is municipal funding in Brazil that is influenced by ecosystem management quality; in this case the allocation of tax revenues is performance based (see Box 8-3).

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Box 8-3. Environmental Indicators in Allocating Tax Shares to Local Governments in Brazil

In Brazil, part of the revenues from a value-added tax (ICMS) collected by state governments must be redistributed among municipalities. Three-quarters of this is defined by the federal constitution, but the remaining 25% is allocated by each state government. The state of Paraná introduced the ecological ICMS (ICMS-E) in 1992, followed by several other states. It was introduced against the background of state-induced land-use restrictions (protected areas) for several municipalities, which prevented them from developing land but provided no compensation. For example, 90 percent of the municipality of Piraquara is designated as a protected area for conserving a watershed to supply the Curitiba metropolitan region with water (May et al. 2002).

Although the states have different systems in place, there are many commonalities in the allocation mechanism. Revenues are allocated according to an ecological index based on the proportion of a municipality's area set aside for protection. Protected areas are weighted according to different categories of conservation management ranging from 1.0 (for ecological research centres and biological reserves) to 0.1 (for special local areas of tourist interest, and buffer zones). Paraná and some other states include an evaluation of the quality of the protected areas in the calculation of the index based on physical quality, biological quality (fauna and flora), quality of water resources, physical representativeness and quality of planning, implementation and maintenance.

Evaluations in Paraná and Minas Gerais show that the introduction of the ICMS-E has been associated with improved environmental management and the creation of new protected areas (May et al. 2002). The ICMS-E has also improved relations between protected areas and the surrounding inhabitants, as they start to see these as an opportunity to generate revenue, rather than an obstacle to development. The ICMS-E has built on existing institutions and administrative procedures, and thus has had very low transaction costs (Ring 2008).

_____ END BOX 8-3 HERE _____

A number of other innovative financial mechanisms may be used to support urban adaptation. These include revolving funds and the energy services company (or the "ESCO") model (OECD 2010:Ch. 8 and Ch 9). Revolving funds can be developed from a variety of different revenue streams, say from a Clean Development Mechanism project (Puppim de Oliveira 2009) or financial savings from energy efficiency investments in municipal buildings, to feed a public fund that can support public investments that yield adaptation benefits. Local governments in high and some middle income countries may also have direct access to debt instruments such as bond markets or loans from national (or regional) development banks or financial institutions (OECD 2010, EIB 2011). Local access to capital markets to fund adaptation investments can also be facilitated through risk-sharing mechanisms or financial guarantees provided by external or domestic development banks e.g. Kfw provides low-interest loans to local banks which in turn finance energy efficiency renovations in residential and commercial building (OECD 2010, Kfw 2011). Funding for climate change adaptation in cities is usually oriented towards technological investment and capital projects, rather than to integrating economic and social approaches. A key challenge is to determine how far adaptation funding should be recalibrated to better take advantage of inputs from social, economic and behavioural sciences and target associated policy realms. For example, the very high costs brought by extreme weather events in urban areas, described in earlier sections, and the fact that climate change increases these risk indicates the need for increased funding and attention from national budgets for disaster risk reduction, early warning and evacuation procedures within urban areas, alongside other adaptation measures (World Bank 2010a, 2010f, Hallegatte and Corfee-Morlot 2011). The urban funding gap may be particularly wide for "soft" rather than "hard" infrastructure investments yet they can be a motor for resilience.

8.4.3.2. Multilateral Humanitarian and Disaster Management Assistance

The international humanitarian community is increasingly active in urban contexts. The scale and scope of action is often impressive, particularly when large disasters unfold in major urban areas. There is opportunity for humanitarians to learn from non-climate related disasters (earthquakes, tsunamis and technological or military events), and the sector is beginning to review experience and develop appropriate tools and guidelines for urban contexts (eg ALNAP, 2012). In 2009 the Inter-agency Standing Committee, an umbrella group of humanitarian groups that sets policy for the aid community, formed a reference group on meeting humanitarian challenges in urban areas, setting a two-year action plan in 2010. It has developed a database of urban specific aid tools, the Urban Humanitarian Response Portal (http://www.urban-response.org/). The complexity faced by humanitarians working in urban areas makes it difficult to target aid to risk reduction or response. One report concludes that the humanitarian sector needs to make better use of social sciences and urban planning in humanitarian teams to better understand urban settings (Grűnewald et al, 2011). Amongst the biggest challenges facing the sector working in urban contexts is to develop policies sensitive to the needs of internally displaced urban populations, and how this can be managed in contexts where the resident population is chronically poor (Zetter and Deikun, 2010); also how international agencies can respond appropriately to the prospect of a significant increase in urban food insecurity (see IRIN, 2013).

The systematic programming of climate change adaptation into multilateral humanitarian, disaster response and management funding is in its infancy and urban dimensions are largely under-developed although this is changing (see United Nations 2009, 2011, IFRC 2010). The World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) explicitly includes adaptation to climate change and its Country Programmes for Disaster Risk Management and Climate Change Adaptation 2009-2011 also seek to deepen engagement in selected priority countries (GFDRR 2009). The GFDRR has also worked with UNISDR to advocate for more joined up policy and advisory services at the technical level (see Mitchell et al. 2010). A survey of 2009-2011 reports from 82 governments on how they were advancing disaster risk reduction and the treatment of urban and climate change issues within this, found that some progress has been made in both areas, across different types of countries (i.e. from low to high income) (Figure 8-3, United Nations 2011).

[INSERT FIGURE 8-3 HERE
Figure 8-3: Progress reported by 82 governments in addressing some key aspects of disaster risk reduction by countries' per capita income.]

Despite such progress, many urban governments lack the capacity to address disaster risk reduction and management. Almost 60 percent of the countries surveyed by the UN and almost 80 percent of lower-middle income countries reported that local governments have legal responsibility for disaster risk management, but only about a third confirmed dedicated budget allocations and these were mostly in upper middle and high income countries (United Nations 2011). Figure 8-3 highlights a relative lack of attention to urban and land-use planning and greater attention to investments in drainage infrastructure. As a whole, attention to these linkages is lower in low and lower-middle income nations, yet in more than half the high to lower middle-income nations, governments reported progress to integrate climate change policies into disaster risk reduction.

8.4.3.3. International Financing and Donor Assistance for Urban Adaptation

To date international adaptation financing has largely overlooked urban areas (UN HABITAT 2011) and most of the most vulnerable cities and municipalities are not well positioned to access available funding (ICLEI, 2010, Paulais and Pigey 2010). This generates a double funding gap – low availability of fundsfor adaptation and often very large deficits in risk-reducing infrastructure and services.

While more international funding for adaptation and mitigation is being committed (see for instance the Cancun Agreements) and there are some indications that governments are broadly on track to deliver on these (Clapp et al. 2012 , Buchner et al. 2011), there is less in evidence is the institutional arrangements by which such support is available to urban governments for adaptation – and thus to support work that can build adaptive systems for urban management, systems that evolve with changing social and environmental dynamics as indicated in the IPCC SREX report (IPCC, 2012). The failure to explicitly recognise urban adaptation needs is also the case for new dedicated climate change funds. In addition, international public funding for adaptation may be difficult to discern from development finance (Tirpak et al. 2010, Buchner et al. 2011).

Recent data suggest that a notable yet still minor share of development finance targets climate adaptation (UNEP 2010, OECD 2012). The extent to which urban adaptation is explicitly or even indirectly covered in donor portfolios is largely unknown, although many bilateral agencies choose to have a very limited engagement with urban initiatives (Satterthwaite and Mitlin, 2013). OECD estimates that between 23-38% of reported ODA commitments from bilateral donors for climate change target adaptation (OECD 2012). In an in-depth assessment of five major donors, with coverage of concessional (ODA) and non-concessional finance, adaptation was estimated to be 30% of the climate change portfolio, most of it targeted to water and sanitation (about 75%) while the remainder targeted urban relevant sectors (i.e. transport, policy loans, disaster risk reduction) with energy and health seemingly largely overlooked (UNEP 2010, see also Atteridge et al. 2007). Conventional multilateral and bilateral channels for development finance appear to have the biggest role in adaptation financing, though several new vertical funds are also emerging. The proliferation of multiple, single purpose funding mechanisms runs contrary to long-standing principles of sound development cooperation notably harmonisation and alignment (McKenzie Hedger 2011). This also creates a more complex funding architecture, making it difficult for smaller actors, such as local authorities, to access available sources for timely adaptation investments.

Reconciling external resources with bottom-up, locally based planning and project preparation could provide a means to better target development assistance (i.e. to urban planning processes that take climate risks into account), while also ensuring that limited funding is directed to programmes that aim to be mainstreamed into urban development over time (Brugmann 2012). Yet research shows that partner countries typically lack defined priorities for the use of funds; when combined with a donor tendency to “control” funds to ensure short-term results, and a large variety of different funding instruments, the result is highly fragmented delivery systems that lead to unclear outcomes (Peskett and Brown 2011). Even where national leadership and climate strategies exist to guide action – as in the case of Bangladesh, an “early mover” on adaptation planning – the plan is not yet costed nor is it sequenced. This makes it difficult to use as a framework for delivery of international climate finance (McKenzie Hedger 2011). A key to improving effectiveness of international public finance will be building the capacity for country-led planning processes that identify priority projects and programmes for the targeting of adaptation funds that include urban adaptation.

National Adaptation Plans of Action (NAPAs) have become a principal way of organising an integrated, climate change aware approach to development but the majority of plans do not explicitly include urban adaptation projects.UN-Habitat's review of a quarter of submitted NAPAs in 2011 found that only 14 per cent of the resources called for by those NAPAs were for projects that were largely or exclusively urban (UN HABITAT 2011c). NAPAs remain essentially top down, led by the national government. Urban governments typically only have access to international public finance through their national governments. One possible approach is for national governments to set up funds that are supported by international finance and on which urban governments can draw (Paulais and Pigey 2010).

A growing consensus among authors concludes that international development finance is failing to tackle urban adaptation financing needs (Parry et al 2009,Paulais and Pigey 2010, UN-Habitat 2011c, ICLEI 2011a). In some middle income countries, such as Indonesia, rather than focusing on large amounts of new external funding to support climate action, a more effective and sustainable strategy may be national fiscal policy reforms and incentives to steer investment to priority needs (Peskett and Brown, 2011). Beyond better delivery and use of development finance, there is also a need to mobilise domestic public and private investment to ensure delivery of adaptation at national and urban levels (Hedger 2011a & b, Hedger and Bird 2011, OECD 2012). Accessing international development finance for urban adaptation will require building routine institutional mechanisms for supporting multilevel planning and risk governance (Corfee-Morlot et al. 2011, Carmin et al, 2013).

8.4.3.4. Institutional Capacity and Leadership, Staffing, and Skill Development

A critical factor of generating interest in urban adaptation is leadership, for example from the Mayor's office or from entrepreneurial staff that understand the challenge and champion awareness raising and institutional change to bring action (Anguelovski, Carmin 2011, Carmin et al. 2012). Creation of a climate change and environmental focal point or office in a city can help to champion and coordinate climate action across government departments or line management agencies (Roberts 2008a, 2010, Anguelovski, Carmin 2011, Hunt and Watkiss 2011, OECD 2011, Brown et al. 2012). Yet there may be downsides when the urban climate change function is housed by the environmental line department (e.g. Durban - Roberts, 2008 :523, Boston see Boston 2010, Sydney see Measham et al. 2010). Roberts (2010) notes that urban environment line managers or departments are typically among the weakest parts of city government. This in turn can marginalise the climate change coordination function to the low or lower priority and limited resources are usually assigned to environmental departments within government structures, which results in limited institutional influence.

Although there is growing evidence of adaptation leadership in urban contexts (Anguelovski and Carmin 2011, Lowe et al 2009, Carmin and Anguelovski 2009, Foster et al., 2011b), there are also important political constraints to making adaptation decisions at the local level. Local government decisions are often driven by short term priorities and nearer term concerns about economic growth and competitiveness, making it difficult for them to focus on the more distant implications of climate change (OECD 2009, Romero Lankao and Qin 2011, Pelling 2011A). Powerful vested interests may oppose attention to adaptation and can promote development on sites at risk (e.g. coastal or river-side real estate developments). A key step forward is to work towards institutionalising different types of behaviour and norms to recognise and act upon climate and disaster risk (Figure 8-4).

[INSERT FIGURE 8-4 HERE
Figure 8-4: The basic challenge of effective climate change communication to change behavior and norms.]

Beyond goal setting and planning for adaptation and disaster risk management, governments also need a regulatory framework that ensures relevant behaviour and investment, creates job descriptions that require actions and provide incentives to act in new ways (e.g. for line managers and sector policymakers); they also need to provide training for staff and clear guidance on what to do (Moser 2006). Establishing budgetary transparency and metrics to measure progress on adaptation will also help to institutionalised changes in planning and policy practice (OECD 2012).

8.4.3.5. Monitoring and Evaluation to Assess Progress

Tools for monitoring and evaluation of urban adaptation actions are needed to assist adaptation leaders and funding institutions to justify investments. Monitoring urban adaptation activities and their effectiveness requires indicators that show if adaptation is taking place, at what pace, and in what locations. Among the relevant evaluation criteria to track are: cost, feasibility, efficacy, co-benefits (direct and indirect), and institutional considerations (Jacob et al. 2010). Assessment methods can capture outcomes of adaptation decisions, or the decision-making processes themselves, and ideally both. Monitoring is particularly challenging for urban adaptation given that there are no standard metrics to assess progress (Lamhauge et al. 2011, GIZ et al. 2012).

City authorities, NGOs and researchers have begun to design adaptation monitoring and evaluation frameworks. Coordinated development of tools offers scope for international benchmarking and comparison and coordination across scales of assessment, for example by associating local indicators of resilience with international ones attributed to the Hyogo Framework for Action and post-2015 agenda (IFRC, 2011). Box 8-4 presents the experience of monitoring from New York City.

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Box 8-4. Adaptation Monitoring: Experience from New York City

Jacob et al. (2010) describe an adaptation monitoring approach developed for New York City. This has four indicator elements: (1) physical climate change variables; (2) risk exposure, vulnerability and impacts; (3) adaptation measures; and (4) new research within each of these categories. Examples of climate change adaptation indicators arising from these four categories include: the percentage of building permits issued in any given year in current FEMA coastal flood zones, and in projected 2080 coastal flood zones; an exact tally of building permits that have measures to reduce precipitation runoff; an index based on insurance data that measures the insurer's perception of New York City's infrastructure-coping capacity; an index that measures the rating of bonds issued by the City or infrastructure operators for capital projects with climate change risk exposure; the detailed trend of weather-related emergency/disaster losses (whether insured or uninsured, relative to the total asset volume); and the number of days with major telecommunication outages (wireless versus wired), correlated with weather-related power outages.

_____ END BOX 8-4 HERE _____

The New York experience has demonstrated that once monitoring is in place new demands for data can refine existing data collection systems including a preference for long-term data sets that span a range of disciplines. This has additional benefits for adaptive planning. In the New York case this need was resolved through data criteria decided through a scientist-stakeholder consensus with designated groups used to evaluate prospective indicators and their values. With its focus on data and processes required to monitor progress on urban adaptation, this case study shows the need for interdisciplinary and longitudinal data collection and analysis systems along with an inclusive and transparent process for stakeholder engagement to interpret the data as part of new monitoring programmes.

A more established aspect of monitoring and evaluation focuses on the effectiveness of donor aid on climate adaptation (Chaum et al. 2011). Recent work shows that consistent and internationally harmonised data collection is urgently needed to support monitoring, this is a concern for adaptation and wider disaster risk reduction spending suggesting a systemic challenge to the architecture of international finance (Kellett and Sparks, 2012). Steps are being made in this direction through multi-site assessment programmes and in some instances this includes treatment of urban issues. For example, the World Bank has recently included an adaptive capacity index as part of an analysis of risk and adaptation options for five cities in Latin America and the Caribbean; the methodology was applied before this to Guyana where it demonstrated a gap between national and city level adaptive capacity (Pelling and Zaidi, 2013).

Monitoring also needs to consider the delivery and use in cities of available international climate finance to ensure that funds are being directed in an effective manner (Hedger 2011, Buchner et al. 2011). This is especially important for cities at an early stage of planning, implementing and monitoring of adaptation, as they can learn from one another's experiences. There is some evidence of an increasing burden of reporting falling on partner organizations and countries, in some cases city authorities, who receive international support, where partners have to devote significant time and human capacity to reporting on progress; reporting may carry high transaction costs, which in turn can detract from further programme design and implementation.

Thus, in reviewing the development of urban adaptation interventions and strategies, do or will they:

- Have potential co-benefits with sound development, disaster risk reduction and ecosystem-based adaptation?
- Reduce mortality and help reduce illness and injury and/or their impacts especially on low-income and vulnerable groups?
- Make livelihoods more resilient and improve choices on employment and livelihoods?
- Meduce negative impacts on economic output and urban centres' capital stock?
- Increase the resilience of lifeline physical and social infrastructure and services?
- Increase the resilience of housing, especially for people with limited incomes and assets?
- Mitigate impact and improve the productivity and resilience of ecosystem services?
- Have potential co-benefits with poverty reduction and mitigation interventions and prepare the base for transformatory adaptation and the reduction of intergenerational risk transfer

8.5. Conclusions

8.5.1. Introduction

Urban areas are and increasingly need to be at the forefront of climate change adaptation and mitigation agendas. They house more than half the world's population and concentrate most of its assets and economic activities. Urban-based activities generate a high proportion of global greenhouse gas emissions so urban policies are key to addressing mitigation. Urban centres also concentrate a high proportion of the populationand economic activities most at risk from climate change and most in need of adaptation. Most of the increase in the world's population and much of the increment in capital formation, economic activity, infrastructure development, ecosystem degradation and emissions is projected to take place in urban areas in low- and middle income countries.Urban centres are thus places where the present and future well-being and safety of humanity must be secured in the face of the increasing uncertainty generated by climate change and other socio-ecological challenges (da Silva et al 2012).

The key role of urban governments in climate change adaptation has become more widely recognized. One example of this is the signing of the Durban Adaptation Charter in December 2011 by 107 mayors representing over 950 local governments at COP17. This signalled their intention to begin addressing climate change adaptation in a more concerted and structured way and is indicative of the climate change leadership being shown by local governments around the world (Rosenzweig et al 2010). But as this chapter has described, the way forward is not simple, with both climate change and climate change adaptation being acknowledged as highly complex and difficult to resolvein most urban contexts (Martins and Ferreira 2011, Fünfgeld and McEvoy 2011). As yet, only a small proportion of urban governments have begun to act on adaptation, often with variable levels of national support.

Because of the complexities and uncertainties involved, action has been limited and focused mostly 'no-risk' and 'low cost' interventions that have adaptation as a co-benefit of existing work streams, rather than a new, stand alone work area (Roberts 2008a, Toronto Environment Office 2008, Runhaar et al 2012). This 'business-as-usual with climate benefits' approach has resulted in a focus on interventionist and reactive infrastructure or asset-oriented adaptation (e.g. LCCP 2006, Awuor, et al., 2008, Mehrotra et al. 2011a, Mees and Driessen 2011) rather than on the 'soft' or process (i.e. human, institutional and ecological) elements of adaptation, such as resilient development, good governance, poverty reduction, livelihood security, social cohesion and ecosystem based adaptation (Lwasa 2010, Jones et al. 2010). A focus on adaptation measures rather than on building adaptive capacity or resilience is especially problematic in urban areas of the global South where it is "limited by resources, weak institutions,

poor/inadequate infrastructure and poor governance" (Kithiia 2009:19). This suggests a need to shift from looking at "what a system *has* that enables it to adapt, to recognising what a system *does* to enable it to adapt" (Jones, et al2010:1). This in turn implies a need for more open-ended and flexible concepts such as adapting well, climate smart, sustainable adaptation and resilience (Eriksen and Brown 2011, Wilson and Termeer 2011, Brown et al. 2012).

This socio-institutionalemphasis also encourages a more transformative view of adaptation. It shifts from being a tool of last resort, or an 'end-of-the-pipe' and incremental intervention (Roberts, et al. 2012:2; Foster et al. 2011) that supports the prioritisation of existing coping strategies (Heindrichs et al, 2011:216) to one that underscores the need for "bouncing forward" (Shaw and Theobald, 2011; Manyena et al 2012) and a departure from the norm. This is characterised in Table 8-2 as a shift from adaptation to resilience and then transformation (Pelling 2011a). This 'business-unusual' approach is especially important in a world where transgressions of key planetary boundaries such as climate change and biodiversity will take humanity out of the globe's "safe operating" space (Rockström et al. 2009: 1) into an unsafe and unpredictable future. If effective adaptation in urban centres is good development conceived and implemented with adaptation in mind, transformation is adaptation that helps achieve the needed global reductions in greenhouse gas emissions and other drivers of anthropogenic climate change. This requires changes to the "fundamental attributes" of existing technological, governance, planning, economic, cultural and value systems(IPCC 2011; Costanza et al 2012, O'Brien, 2011, Pelling 2011a).

8.5.2. What Hinders Adaptation Progress in Urban Areas?

Lack of mandate: There is a need to clarify which sphere (national, provincial, metropolitan and urban) of government has a legal mandate to act on climate change through the promulgation and assignment of appropriate constitutional and legal powers. Without these formal mandates, adaptation becomes an optional and discretionary extra, dependent on local level interest and resources and particularly vulnerable to leadership change. Although much of the innovation in adaptation and mitigation has come from particular local governments, for these to become effective at a national scale and to ensure coherence and widespread implementation, support from higher levels of government is required (Kazmierczak and Carter 2010, also Carter 2011, Brown 2011, Martins and Ferreira 2011). Where mandates exist, they have been important in driving local level action (Kazmierczak and Carter 2010) but they need increased co-ordination and co-operation if they are shared between the different spheres of government (Martins and Ferreira 2011, Carter 2011) or cross jurisdictional boundaries. New mandates (formal or informal) may also require institutional changes(Lowe *et al*. 2009, Roberts 2008a, Kazmierczak and Carter 2010).

Political obstacles: Decisions in urban centres including those related to climate change adaptation, are affected by political interests and competition for support (Mees and Driessen, 2011, Brown et al, 2012). Those who are most at risk from climate change are often those with the least voice and influence on these decisions. Addressing constraints such as information and resources alone will not ensure transformation if there is political resistance, particularly as politicians control local level resources (Roberts 2008a). A further complication is the disjuncture between political and climate time lines (Mees and Driessen, 2011). This sets short-term (often personal advancement) priorities against the inter-generational and public good impacts of climate change adaptation, making communicating and negotiating climate change related objectives in the political space often very difficult to achieve (UN-Habitat 2010).

The weakness of climate change focal points within local government: These are often housed in or championed by environmental line department which usually leads to marginalisation (Roberts 2010, Hardoy and Romero Lankao 2011) and limited institutional influence and access to resources given the low priority usually assigned to environmental departments. There is also a concern that in the current recession, that local authorities(with already limited resources) will prioritise conventional economic and development goals over 'environmental' issues including climate change adaptation(Shaw and Theobald 2011, Solecki 2012).

Undervaluing community resources and social capital: Although 8.4 gives examples of the effectiveness of household and community based adaptation in urban contexts, there is still limited work and limited understanding of the potentials and limitations (Jones et al. 2010). This is a critical gap given that social capital and community

based adaptation may provide opportunities to achieve the "bouncing forward" required by adaptation, as community collaboration, relationships and trust can provide a platform to generate material interventions directed at reducing vulnerability (Kithiia 2009). The issue of social capacity has been identified as important to urban resilience in a number of urban areas (TARU 2011, Roberts 2010) but there is also a need to determine the limits of community based intervention; for example, communities cannot install, maintain and fund trunk infrastructure and the scale and scope of needed service provision at city and city-region scales.

The complexities of developing locally relevant adaptation plans: Mitigation-focused interventions provided the first experiential training for most local governments engaging with climate change. These were often based on step-wise guidebooks or programmes (e.g. ICLEI's Cities for Climate Protection Programme, UN-Habitat's Planning for climate change manual) (Anguelovski and Carmin 2011, Martins and Ferreira 2011). Experience with adaptation programmes show they are less open to a standard set of requirements, given that actions are oftencross-sectoral, cross-institutional, complex, operating across a range of scales and timelines,rooted in local contexts,involve more stakeholders and include high levels of uncertainty (Roberts et. al. 2012, Roberts and O'Donoghue 2013). More than standardised guidelines, urban adaptation practitioners need clarity, creativity, and courage (ICLEI Oceania 2008).

Dealing with uncertainty: Adaptation costs areimmediate, a fact which contrasts with the uncertainty associated with climate change projections (see 8.2.5.1.) and the possible delay in the benefits (OECD 2010). A pragmatic approach is therefore to focus on existing vulnerabilitiesand to use those to identify 'no-regrets' options with near and long-term co-benefitssuch as enhanced competitiveness, improved service delivery, economic resilience (and success), job creation and risk management as these help get the attention of politicians and decision makers (e.g. Durban, London, New York and Copenhagen) (Foster et al. 2011, Roberts 2010, GLA 2011, City of New York 2011, City of Copenhagen 2011, Runhaar et al , 2011).The use of scenario planning as a possible alternative to scaled down projections, the undertaking of further studies to develop better local data and understand the costs of inaction, avoiding maladaptation and increasing awareness also contribute to increased adaptive capacity (Tyler et al. 2010, OECD 2010, TARU 2010, Neimi 2009). Facilitating networking and learning between adaptation practitioners also assists in improving the capacity to deal with uncertainty (Mees and Driessen, 2011).

The issue of thresholds and conflicting agendas: Most local governments acknowledge the value of mitigation and adaptation, but to lead with one or the other depending on circumstances, priorities, resources and institutional affiliations (Roberts 2010, Carmin et al. 2012, Hamin 2011, Moser 2012). The result is that little progress has been made in ensuring that adaptation and mitigation policy goals are not in conflict (Hamin and Gurran 2009, Moser 2012). Section 8.3.3.7 discussed what Hamin and Gurran, 2009 described as the "density conundrum" where the densities that serve mitigation can prevent or limit the possibilities of ecosystem based adaptation and may also exacerbate the urban heat island and limit the possibility of utilizing solar energy. There is therefore an urgent need for research to determine the thresholds for unacceptable biodiversity change and to derive from these locally specific limits to urban densificationand ensure that climate actions do not undermine other global environmental change agendas such as biodiversity protection (Moser 2012). The issue of thresholds is also relevant beyond biodiversity concerns, for example, determining when and where adaptation is no longer possible in urban areas, due to technical difficulties or cost (or both) resulting in residual damage (UN-Habitat 2011c, Parry et al. 2009). This knowledge about limits within existing systems will be vital in developing appropriate planning responses to future climate challenges, especially as there is increasing concern that the current state of global inaction and lack of ambition on mitigation could result in 4 degrees or more of global warming, necessitating a "more substantial, continuous and transformative process" of adaptation (Smith et. al. 2011:196). This also raises the possibility of abrupt, non-linear and unpredictable global environmental change (Rockström et al. 2009) that will stretch the adaptive capacity not only of existing urban systems, but of the whole global system.

8.5.3. What Contributes to the Development of Effective Transformative Adaptation Plans?

Building on future urbanization opportunities: United Nations projections suggest that in the next 40 years, the world's urban population will nearly double (United Nations 2012) requiring the same scale of urban infrastructure be built in 40 years as in the past 4000 years (ICLEI, 2011b). This provides a transformative opportunity at a global level, especially in the global South with its large infrastructural deficits, to break away from unsustainable lifestyles

and patterns of development and ensure that urban areas develop in ways that acknowledge that "natural capital and ecosystem services are not infinitely substitutable, and real limits exist" (Costanza et al 2013). This represents a significant opportunity to urbanise the adaptation agenda, and converge climate mitigation and adaptation actions within an understanding of a "full-world" context (Costanza et al 2013).

Prioritising poverty reduction within climate change responses: While cities like Boston and London consider low-income groups among the vulnerable groups in their planning (Boston 2011, GLA 2011) for most cities and smaller urban centres in low and middle-income nations, poverty reduction needs more attention because of its greater scale and depth and because of the strong association between poverty and poor environmental health (Hardoy et al. 2001), disaster risk (United Nations 2009) and climate change risks (Hardoy and Pandiella 2009). Given this and the pressing development needs in these urban centres (e.g. infrastructure, health care and emergency services, education, housing and energy), climate change adaptation needs are often viewed as marginal in comparison. There is therefore a need to work within the development context of each country and urban area (Kithiia and Dowling 2010, Roberts 2008a) and to demonstrate how adaptation can support development that is safe and cost effective (Kazmierczak and Carter 2010) and prioritises poverty reduction, disaster risk reduction and resilient service provision (Kithiia 2010, da Silva et al 2012).

*Reducing risk can provide a compelling vehicle for adaptation action (*see 8.3.2.2). This can occur by responding to existing challenges (for instance extreme weather events) and opportunities (for instance disaster risk reduction after a disaster that 'builds back better' - see Lyons 2009) in ways that enhance adaptive capacity (Kazmierczak and Carter, 2010, Solecki 2012). Experience to date on this is mixed. It is influenced by differences in risk perception and how successfully disaster risk reduction and adaptation become embedded within local development processes and the extent to which they address the structural causes of vulnerability(UN-Habitat 2010, Pelling 2011a, Roberts and O'Donoghue 2013). There is also a widespread assumption that sound urban development and the provision of basic services is sufficient to reduce risk to climate change, but there is a need to interrogate the effectiveness and limitations of current models of infrastructure and service provision. Adaptation can benefit from disaster risk reduction's more detailed, locally rooted analyses of risk and vulnerability and its recognition that most disasters are the result of a failure to identify problems and act. It can also benefit from multi-level government responses to disaster risk reduction that recognize the central role of local government and other local institutions but also the importance of supportive policies, institutions and legislation at higher levels of government. But disaster risk reduction is informed by analyses of past disasters,while adaptation also has to be informed by knowledge of new risks, vulnerabilities and uncertainties.

Incorporating ecosystem based adaptation: 8.3 noted how a growing number of cities are recognizing that biodiversity and ecological integrity can be used to protect people and the resources on which they depend. Ecosystem-based adaptation is regarded as one of the more cost effective and sustainable approaches to adaptation given what needs to be spent to manage and preserve ecosystems and the climate adaptation value derived from that spend (Nature Conservancy TNC 2009, Mees and Driessen, 2011, da Silva et al 2012, Brown et al 2012). But there are considerable knowledge gaps in determining the limits or thresholds to adaptation of various ecosystems and where and how ecosystem based adaptation is best integrated with other adaptation measures. There is also some indication that the costs of ecosystem based adaptation in urban contexts might be higher than expected, in large part because costs are higher for land acquisition and ecosystem management (Roberts et al 2012, Cartwright et al 2013).

Engaging all stakeholders and awareness raising: There is a need for dialogue and opportunities to advance the adaptation agenda through internal and external collaboration. These range from cross-cutting technical advisory groups often with sectoral or task group focal areas (Lowe et al. 2009, Parzen 2008, Boston 2011, City of New York 2011, Mees and Driessen, 2011, Solecki, 2012) to more broadly representative multi-stakeholder or multi-departmental groups with a core working group (Tyler et al. 2010, Roberts 2010, Brown et al. 2012, Boston 2010, Kazmierczak and Carter 2010, Anguelovski and Carmin 2011). Equally important is building public awareness and support for adaptation as transformation "neighborhood by neighborhood" (Foster et al. 2011, also Kazmierczak and Carter 2010). This is especially important where large sections of the population live and work in informal settlements and include a high proportion of those most at risk from climate change.

Institutional and social learning: For all urban centres, successful adaptation requires a learning organization that adapts to changing environmental factors and incorporates new data on a regular and flexible basis – producing an iterative process of learning about changing risks and opportunities and drawing in different stakeholders (Brown et al 2012). This is difficult to achieve with weak governmental structures, lack of funding and trained staff, where "decisions are delayed, correspondences lost in bureaucratic black-holes and ascription of responsibility is obfuscated" (Kithiia 2009, also Brown 2011). Social learning is also critical to ensure new ideas are popularized and commonly articulated in society (Pelling 2011a), translating stakeholder engagement into adaptation action.

The importance of mainstreaming climate change adaption requirements into municipal planning and land-use management systems: This chapter opened with an acknowledgement that local governments must provide the planning, management and regulatory frameworks to ensure that investments and actions by businesses and households contribute to adaptation (Kazmierczak and Carter 2010, Brown 2011, Mees and Driessen, 2011, Sussman et al., 2010). But this must avoid overloading already complex and inadequate planning systems (Kithiia 2010, Roberts 2008a) stressed by lack of information, institutional constraints and resource limitations with unrealistic new requirements. Mainstreaming adaptation ensures that limited financial resources are spent "with adaptation needs in mind" (Lowe et al. 2009) and fosters a move to a risk-based design for a range of future projected climate conditions. This can be enhanced by encouraging each sector to consider its need for and role in adaptation action. A sectoral approach makes the climate message easier for local governments and other stakeholders to understand and the associated responsibilities and actions clearer and simpler to identify and assign (Roberts 2010, UN-Habitat 2011a, Roberts and O'Donoghue 2013). As each sector in local government comes to understand its roles and responsibilities, so the basis for integration and cross-sectoral coordination is formed.

The importance of champions. Champions, regardless of their location or affiliation are important in driving successful adaptation action (Kazmierczak and Carter 2010). The role of local government champions has often proved critical in providing initial leadership (e.g. Sydney, Chicago, New York, Durban, London) and promoting and sustaining the adaptation agenda both at a sectoral level (e.g. Durban) and in buildingbroader institutional memory and purpose (e.g. Chicago, Toronto)(Lowe et al. 2009, Roberts 2008a, Parzen 2008, Rosenzweig and Solecki 2010, Shaw and Theobald 2011, Anguelovski and Carmin 2011, Carmin et. al. 2012, Mees and Driessen, 2011, Martins and Ferreira 2011, Roberts and O'Donoghue 2013). This may face a lack of continuityas champions change position orleave office. It is important to plan for this so that progress is not stalled or undermined. This can be helped by developing a broad base of support for adaptation across many sectors - within and outside government and other local stakeholders such as civil society groups or universities can help ensure continuity (Hardoy 2013).

The need for scientific support andan evidence base for adaptation action (Lowe et al*,* 2009, Roberts 2008a, Kazmierczak and Carter 2010, Horton et al 2011, Blake et. al, 2011, Moffet et al 2011):Despite growing attention, useful information and assessment of climate change at urban spatial scales is still lacking (Hunt and Watkiss 2011; Kehew 2009). Local governments need to access reliable, accurate, useable scientific data. Even where these are available, their staff often cannot utilize them because of the language gap between information producers (scientists) and information users (local decision makers) (Lowe et al. 2009, Opitz-Stapleton 2010). Practitioners often relymore on informal information sources and formats such as colleagues and the internet (Corfee-Morlot et al. 2011). Here, local risk assessments of existing hazards, challenges and vulnerabilities that could be exacerbated by climate change offer a useful alternative starting point and facilitate the creation of an appropriate evidence base (Tyler et al. 2010, Kazmierczak and Carter 2010). Collaboration and partnership with researchers and research institutes (especially those with local knowledge) (e.g. Durban,Chicago, Seattle, Manchester) can help each urban centre gainknowledge about climate impacts (Lowe et al. 2009, Kazmierczak and Carter 2010).

Catalytic role of multilateral and bilateral funding: While conventional multilateral development banks and bilateral agencies appear have the biggest role in adaptation financing (Ayers 2009), there is an emerging argument that finance for urban resilience and adaptation needs to respond to local demands, contexts and possibilities. This poses a challenge to conventional global finance mechanisms that work through national governments to determine which local actions are eligible for funding (ICLEI 2011a, Brugmann 2012). There is also evidence of substantial spend on adaptation from local and national governments in some nations (Kazmierczak and Carter 2010).

Phased approaches: A phased approach is more likely to attract local government attention (Foster et al. 2011, City of Copenhagen 2011, Boston 2011, Wajih et al. 2010, Solecki 2012). In each urban centre, this prioritizes the most urgent matters (usually rapid onset disasters) or near term climate impacts, leaving a longer time period to plan for those impacts that may occur in the future and be associated with greater uncertainty (including slow onset disasters). For slow-onset impacts, strategic forward planning is critical, and existing planning instruments such as land use planning may need to be altered to take changes in climatic stressors into account. Often the initial phases of action are made possible by the existence of previous or current environmental initiatives, or strong environmental traditions at the local level (Kazmierczak and Carter 2010).

Poorly developed Monitoring and Evaluation systems: Monitoring and evaluating the development and implementation of adaptation plans is still evolving (Jacob et al 2010) and not well developed or widely implemented in urban areas (Kazmierczak and Carter 2010). Work is required in this regard, but it is likely to be challenging given the localized nature of adaptation and hence the difficulty of standardizing performance requirements and measurements (Anguelovski and Carmin 2011).

Role of international institutions: The lack of skills and resources in local governments gives international institutions an important role in initiating and shaping the adaptation agenda. These international programmes are often the main form of institutional and financial support to mitigation and adaptation work at local level, although in some local governments internal motivations (e.g. perception of threat, city agendas, leadership, improving city image) (Anguelovski and Carmin, 2011, Carmin et. al. 2012, Kazmierczak and Carter 2010) appear equally influential. The danger of the donor driven model is that the funding agency's agenda may not coincide with local priorities, resulting in little lasting local ownership once support is withdrawn.

Local action involving all local stakeholders, addressing local issues, tapping local knowledge and other resources and respecting local limits is the key to transformative adaptation. Urban areas, because of their size, number, economic importance and social and environmental characteristics, are the geography where this has to happen. So they will have a critical role in the success or failure of the global adaptation project. Mobilising this local level capacity is challenging for international agencies. But if done in ways that are equitable and co-operative and that respect the limits of natural ecosystems, it has the potential to improve human well-being, maximize innovation and help define and implement development paths that converge in a more sustainable and low carbon future.

Frequently Asked Questions

FAQ 8.1: How does disaster risk reduction relate to climate change adaptation?

There is a long experience with urban governments implementing disaster risk reduction that is underpinned by locally-driven identification of key hazards, risks and vulnerabilities to disasters and that identifies what should be done to reduce or remove disaster risk. Its importance is that it encourages local governments to act before a disaster – for instance for risks from flooding, to reduce exposure and risk as well as being prepared for emergency responses prior to the flood (eg temporary evacuation from places at risk of flooding) and rapid response and building back afterwards. In some nations, national governments have set up legislative frameworks to strengthen and support local government capacities for this (see 8.3.2.2). This is a valuable foundation for assessing and acting on climate-change related hazards, risks and vulnerabilities, especially those linked to extreme weather. So urban governments with effective capacities for disaster risk reduction (with the needed integration of different sectors) provides an important component of adaptive capacity. But climate change adaptation needs to take account of how hazards, risks and vulnerabilities will or might change over time. Disaster risk reduction also covers disasters resulting from hazards not linked to climate or to climate change such as earthquakes.

FAQ 8.2: Doesn't good development produce urban adaptation?

Adaptation is well served by good quality infrastructure and services that reach all of an urban centre's population and the institutional capacity to provide, and manage these and expand them when needed. Poverty reduction can also support adaptation by increasing individual and household resilience to stresses and shocks and enhancing their capacities to adapt. These provides a foundation for building climate change resilience but additional knowledge,

resources, capacity and skills are generally required, especially to build resilience to changes beyond the ranges of what have been experienced in the past.

FAQ 8.3: Wouldn't urban problems be lessened by rural development?

The movement of rural dwellers to live and work in urban areas is mostly in response to the concentration of new investments and employment opportunities in urban areas. All high-income nations are predominantly urban and increasing urbanization levels are strongly associated with economic growth. Economic success brings an increasing proportion of GDP and of the workforce in industry and services, most of which are in urban areas. While rapid population growth in any urban centre provides major challenges for its local government, the need here is to develop the capacity of local governments to manage this with climate change adaptation in mind. Rural development and adaptation that protects rural dwellers and their livelihoods and resources has high importance as stressed in other chapters – but this will not necessarily slow migration flows to urban areas, although it will help limit rural disasters and those who move to urban areas in response to these.

FAQ 8.4: Shouldn't urban adaptation plans wait until there is more certainty about local climate change impacts?

More reliable, locally specific and downscaled projections of climate change impacts and tools for risk screening and management are needed. But local risk and vulnerability assessments that include attention to those risks that climate change will or may increase provide a basis for incorporating adaptation into development now, including supporting policy revisions and more effective emergency plans. In addition, much infrastructure and most buildings have a life of many decades so investments made now need to consider what changes in risks could take place during their lifetime. In addition, the incorporation of climate change adaptation into each urban centre's development planning and investments is well served by an iterative process within each locality of learning about changing risks and uncertainties that informs an assessment of policy options and decisions

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Table 8-1: The distribution of the world's urban population by region, 1950–2010 with projections to 2030 and 2050.

Urban population (millions of inhabitants)						
Major area, region, country or area	**1950**	**1970**	**1990**	**2010**	**Projected for 2030**	**Projected for 2050**
World	745	1,352	2,281	3,559	4,984	6,252
More developed regions	442	671	827	957	1,064	1,127
Less developed regions	304	682	1,454	2,601	3,920	5,125
Least developed countries	15	41	107	234	477	860
Sub-Saharan Africa	20	56	139	298	596	1,069
Northern Africa	13	31	64	102	149	196
Asia	245	506	1,032	1,848	2,703	3,310
China	65	142	303	660	958	1,002
India	63	109	223	379	606	875
Europe	281	412	503	537	573	591
Latin America and the Caribbean	69	163	312	465	585	650
Northern America	110	171	212	282	344	396
Oceania	8	14	19	26	34	40
Percent of the population in urban areas						
World	29.4	36.6	43.0	51.6	59.9	67.2
More developed regions	54.5	66.6	72.3	77.5	82.1	85.9
Less developed regions	17.6	25.3	34.9	46.0	55.8	64.1
Least developed countries	7.4	13.0	21.0	28.1	38.0	49.8
Sub-Saharan Africa	11.2	19.5	28.2	36.3	45.7	56.5
Northern Africa	25.8	37.2	45.6	51.2	57.5	65.3
Asia	17.5	23.7	32.3	44.4	55.5	64.4
China	11.8	17.4	26.4	49.2	68.7	77.3
India	17.0	19.8	25.5	30.9	39.8	51.7
Europe	51.3	62.8	69.8	72.7	77.4	82.2
Latin America and the Caribbean	41.4	57.1	70.3	78.8	83.4	86.6
Northern America	63.9	73.8	75.4	82.0	85.8	88.6
Oceania	62.4	71.2	70.7	70.7	71.4	73.0
Percent of the world's urban population						
World	100.0	100.0	100.0	100.0	100.0	100.0
More developed regions	59.3	49.6	36.3	26.9	21.4	18.0
Less developed regions	40.7	50.4	63.7	73.1	78.6	82.0
Least developed countries	2.0	3.0	4.7	6.6	9.6	13.8
Sub-Saharan Africa	2.7	4.1	6.1	8.4	11.9	17.1
Northern Africa	1.7	2.3	2.8	2.9	3.0	3.1
Asia	32.9	37.4	45.2	51.9	54.2	52.9
China	8.7	10.5	13.3	18.6	19.2	16.0
India	8.5	8.1	9.8	10.6	12.2	14.0
Europe	37.6	30.5	22.0	15.1	11.5	9.5
Latin America and the Caribbean	9.3	12.1	13.7	13.1	11.7	10.4
Northern America	14.7	12.6	9.3	7.9	6.9	6.3
Oceania	1.1	1.0	0.8	0.7	0.7	0.6

Source: Derived from statistics in United Nations 2012.

Table 8-2: The large spectrum in the capacity of urban centres to adapt to climate change. One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centres. There are tens of thousands of urban centres worldwide with very large and measureable differences between them in population, area, economic output, human development, ecological footprint and greenhouse gas emissions. The differences in adaptive capacity are far less easy to quantify. This Table seeks to illustrate differences in adaptive capacity and factors that influence it.

<table>
<tr><th>Indicator Clusters</th><th>Very little adaptive capacity or recovery/ 'bounce-back' capacity</th><th>Some adaptive capacity and recovery/ 'bounce-back' capacity</th><th>Adequate capacity for adaptation and recovery/ 'bounce-back' but needs to be acted on</th><th>Climate Resilience and capacity to bounce forward</th><th>Transformation</th></tr>
<tr><td>Population served with risk-reducing infrastructure (paved roads, storm and surface drainage, piped water ….) and services relevant to resilience (including health care, emergency services, policing/rule of law) and the institutions needed for such provision</td><td rowspan="2">0-30% of the urban centre's population served; most of those unserved or inadequately served living in informal settlements</td><td rowspan="2">30-80% of the urban centre's population served; most of those unserved or inadequately served living in informal settlements</td><td rowspan="2">80-100% of the urban centre's population served; most of those unserved or inadequately served living in informal settlements</td><td>Most/all of the urban centre's population with these and with an active adaptation policy identifying current and probable future risks and with an institutional structure to encourage and support action by all sectors and agencies. In many cities, also address and upgrade ageing infrastructure</td><td>Urban centres that have integrated their development and adaptation policies and investments within an understanding of the need for mitigation and limited ecological footprints</td></tr>
<tr><td>The proportion of the population living in legal housing built with permanent materials (meeting health and safety regulations)</td><td>Active programme to improve conditions, infrastructure and services to informal settlements; identify and act on areas with higher/increasing risks. Revise building standards.</td><td>Land use planning and management successfully providing safe land for housing, avoiding areas at risk and taking account of mitigation</td></tr>
<tr><td>Proportion of urban centres covered</td><td>Most urban centres in low-income and many in middle-income nations</td><td>Many urban centres in many low-income nations; most urban centres in most middle income nations</td><td>Virtually all urban centres in high-income nations, many in middle-income nations</td><td>A small proportion of cities in high-income and upper-middle income nations</td><td>A few innovative city governments thinking of this and taking some initial steps</td></tr>
<tr><td>Estimated inhabitants of such urban centres</td><td>One billion</td><td>1.5 billion</td><td>1 billion</td><td colspan="2">Very small</td></tr>
<tr><td>Infrastructure deficit</td><td colspan="3">Much of the built up area lacking infrastructure</td><td colspan="2">Most or all the built up area with infrastructure (paved roads, covered drains, piped water…..)</td></tr>
<tr><td>Local government investment capacity</td><td colspan="3">Very little or no local investment capacity</td><td colspan="2">Very substantial local investment capacity</td></tr>
<tr><td>Occurrence of disasters from extreme weather[1]</td><td colspan="3">Very common</td><td colspan="2">Uncommon (mostly due to risk-reducing infrastructure, services and good quality buildings available to almost all the population</td></tr>
</table>

[1] See text in regard to disasters and extensive risk (United Nations 2011)

Indicator Clusters	Very little adaptive capacity or recovery/ 'bounce-back' capacity	Some adaptive capacity and recovery/ 'bounce-back' capacity	Adequate capacity for adaptation and recovery/ 'bounce-back' but needs to be acted on	Climate Resilience and capacity to bounce forward	Transformation
Examples	Dar es Salaam; Dhaka	Nairobi, Mumbai	Cities in high-income nations	New York?; London? Manizales?	
Implications for climate change adaptation	Very limited capacity to adapt. Very large deficits in infrastructure and in institutional capacity. Very large numbers exposed to risk if these are also in locations with high levels of risk from climate change	Some capacity to adapt, especially if this can be combined with development but difficult to get city governments to act. Particular problems for those urban centres in locations with high levels of risk from climate change	Strong basis for adaptation but needs to be acted on and to influence city government	City government that is managing land-use changes as well as having adaptation integrated into all sectors	City government with capacity to influence and work with neighbouring local government units. Also with land-use changes managed to protect eco-system services and mitigation
NB: For cities that are made up of different local government areas, it would be possible to apply the above at an intra-city or intra-metropolitan scale. For instance, for many large Latin American, Asian and African cities, there are local government areas that would fit in each of the first three categories					

Table 8-3: The possibilities and limitations of focused activity for community groups on climate change coping and adaptation.

Capacity/Focus of Action	Coping (drawing on existing resources to reduce vulnerability, hazardousness and contain impacts from current and expected risk)	Adaptation (using existing resources and especially information to reorganize future asset profiles and entitlements to better position the household in the light of anticipated future risk, and to prepare for surprises)
Physical – buildings and critical community-level infrastructure	Often possible to improve these although tenants will have little motivation to do so	Amber; limits in how much risk reduction is possible within settlement
Physical – land and environment	Local hazard reduction through drain cleaning, slope stabilization etc is a common focus of community based action(although there are less incentives where the majority of residents are short-term tenants or threatened with eviction) (Green)	External input required to design local hazard reduction works in ways that will consider the impacts of climate change 20 years or more in the future (Amber)
Social – health, education	Many examples of community based action to improve local health and education access and outcomes, often with strong NGO and/or local government support (Green)	Health care and education are amenable to supporting adaptation by providing long-term investments in capacity building. They are rarely framed in climate change adaptation terms (Amber)
Economic – local livelihoods	Livelihoods routinely assessed as part of assessments of coping capacity in urban areas. More rarely is there a local livelihood focus for community based coping (Amber)	Livelihoods and wider economic entitlements are key to individual adaptive profiles, but are seldom considered as part of urban community based adaptation programmes (Red)
Institutional – community organization	Local community strengthening is a common goal of interventions aimed at building coping capacity. Risk mapping, early warning, risk awareness, community health promotion and shelter training are common foci increasingly applied to urban communities. Local savings groups may have important roles. Green	Local community strengthening is a core element of planning for adaptation but there are few assessments of the medium/long-term sustainability of outcomes. Where these have been undertaken close ties to wider civil society networks or supportive local government is evident for community organizations to persist Amber
Institutional – external influence	It is unusual for coping programmes to include an element of external advocacy aimed at changing policy or practices in local government. Amber	Despite being core to determining future adaptation there are very few examples of urban community based adaptation projects that include a targeted focus or parallel activity aimed at shifting priorities and practices in local government and beyond to support community capacity building Red

Key: green = many cases of activity, amber = few cases of activity, red = very few cases of activity

Table 8-4: Main sources of funding and financial instruments for urban adaptation.

Sources of funding	Types	Instruments	Examples of what can be funded	Urban capacity required to access funding
Local - public	Local revenue raising policies: Taxes, fees and charges, or use of local bond markets	♦ Local taxes (eg on property, land value capture, sales, businesses, personal income, vehicles….) ♦ User charges (eg water, sewers, public transport, refuse collection) ♦ Other charges or fees (eg parking, licenses)	♦ Urban infrastructure and services ♦ Urban adaptation programmes and planning processes ♦ Urban capacity building	♦ Cities with well-functioning administrative and institutional capacity and adequate funding from local revenue generation and inter-governmental transfers
Local – public-private	Public-Private-Partnerships (PPP) contracts and concessions	♦ Concessions and private finance initiatives (PFIs) to build, operate and/or maintain key infrastructure ♦ Energy performance contracting	♦ Medium to large-scale infrastructure with strong private goods (to allow rents for private sector)	♦ Cities with strong capacity for legal oversight and management
Local or national - Private or Public	National or local financial markets	♦ Commercial loans, ♦ Private bonds ♦ Municipal bonds	♦ Basic Physical Infrastructure (need for collateral)	♦ Well-functioning local or national financial markets that city governments can access
National - public	National (or state/provincial) revenue transfers or incentive mechanisms	♦ Revenue transfers from central or regional government ♦ PES or other incentive measures	♦ Urban Payment for Environmental Services in Brazil ♦ Sweden's KLIMP Climate Investment programme	♦ Cities with good relations with national governments, strong administrative capacity to design and implement policies and plans
International – private	Market-based investment	♦ Foreign Direct Investment, Joint Ventures	♦ Industrial infrastructure ♦ Power generation infrastructure	♦ Cities with strong national enabling conditions and policies for investment
International sources	Grants, concessional financing (e.g. Adaptation Fund)	♦ Grants, concessional loans and loan guarantees through bilateral and multilateral development assistance ♦ Philanthropic grants	♦ Urban capacity building ♦ Urban infrastructure adaptation planning	♦ Typically requires strong MLG – cities with good relations with national governments ♦ Cities with low levels of administrative and financial market capacity

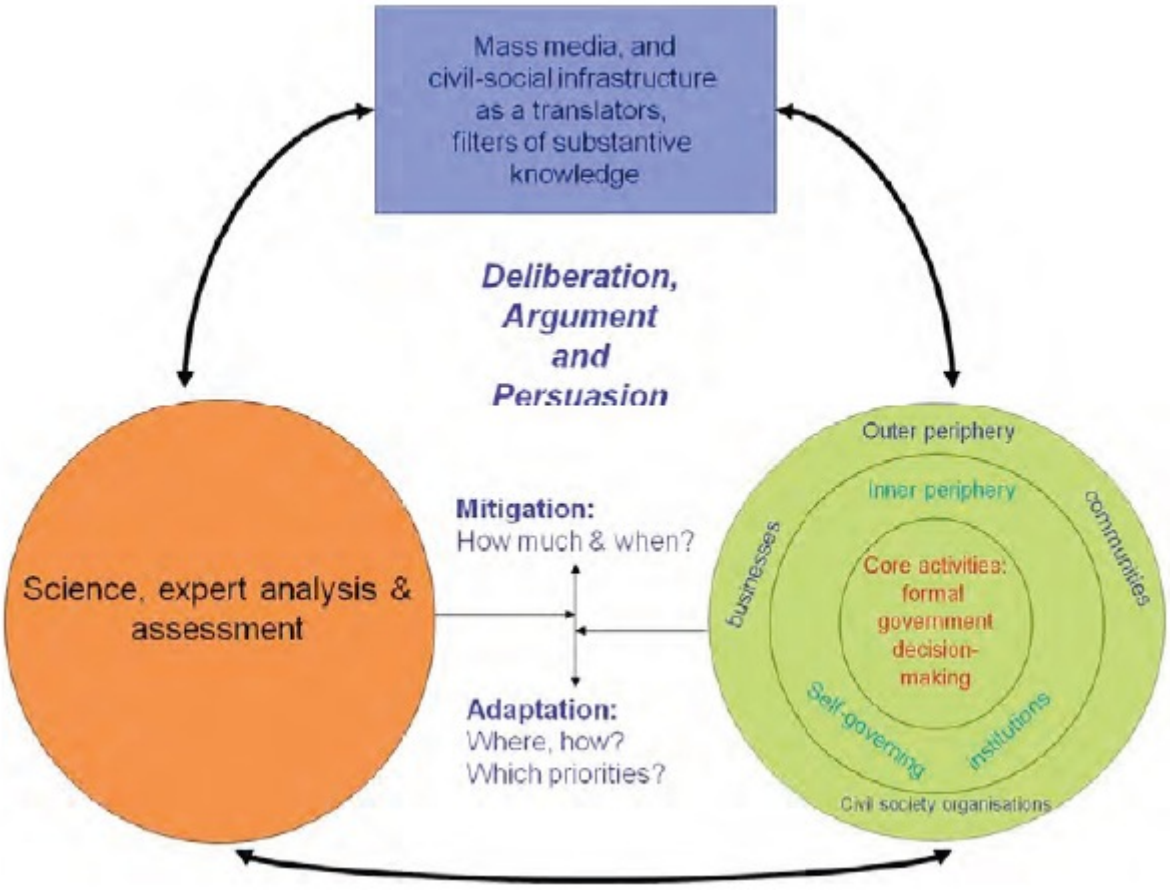

Figure 8-1: Circulation of power for public decisionmaking on climate change. Source: adapted from Corfee-Morlot, Cochran, Teasdale, and Hallegatte, 2011.

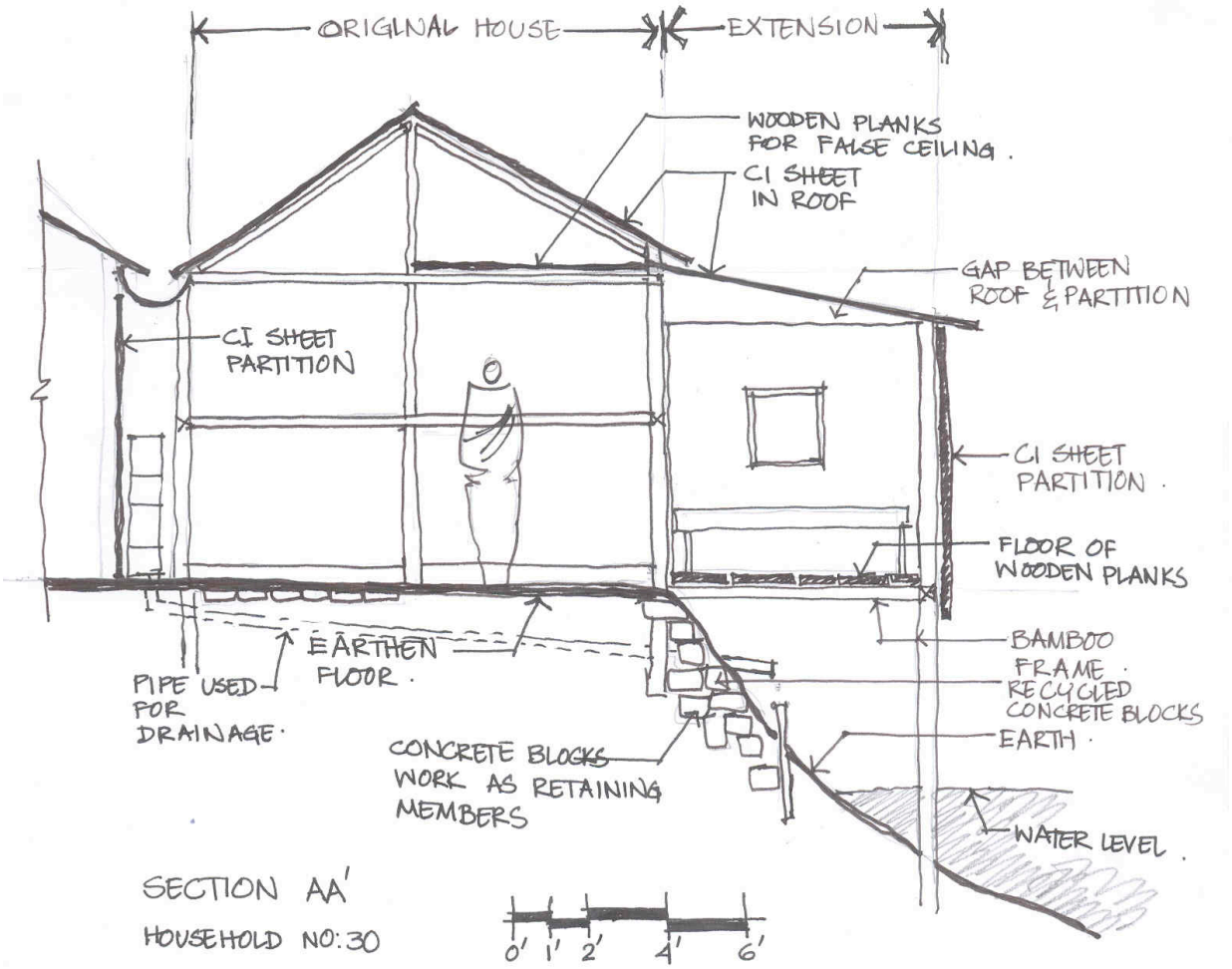

Figure 8-2: Household adaptation - a cross section of a shelter in an informal settlement in Dhaka (Korail) showing measures to cope with flooding and high temperatures. Source: Jabeen et al, 2010.

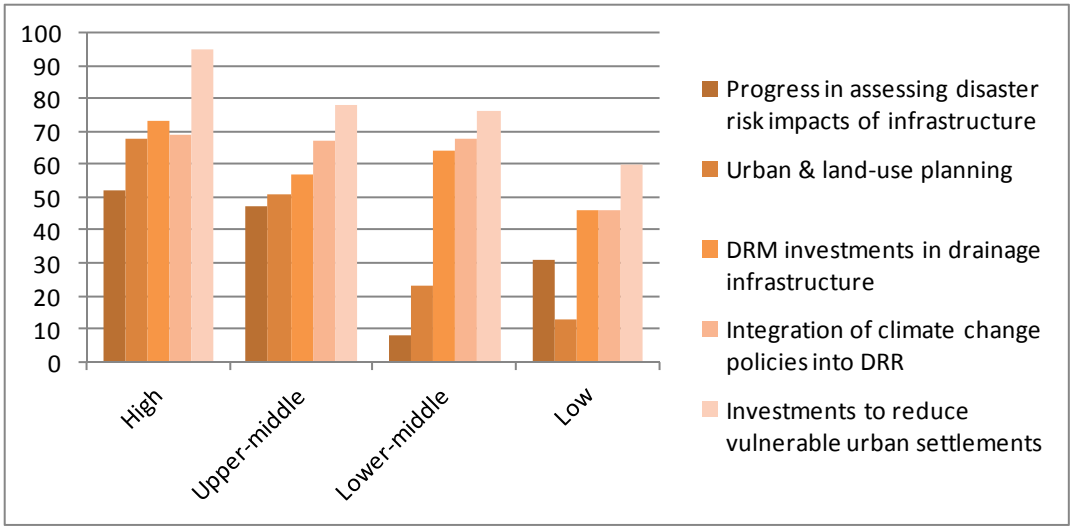

Figure 8-3: Progress reported by 82 governments in addressing some key aspects of Disaster Risk Reduction by countries' per capita income. Source: United Nations, 2011.

Figure 8-4: The basic challenge of effective climate change communication to change behaviour and norms. Source: Moser and Luers, 2008.

Chapter 9. Rural Areas

Coordinating Lead Authors
Purnamita Dasgupta (India), John Morton (UK)

Lead Authors
David Dodman (Jamaica), Barış Karapinar (Switzerland), Francisco Meza (Chile), Marta G. Rivera-Ferre (Spain), Aissa Toure Sarr (Senegal), Katharine Vincent (South Africa)

Contributing Authors
Ashish Aggarwal (India), Netra Chhetri (Nepal), Tracy Cull (South Africa), Jose Gustavo Feres (Brazil), Jeremy Haggar (UK), George Hutchinson (UK), Feliu Lopez-i-Gelats (Spain), Megan Mills-Novoa (USA), Nandan Nawn (India), Catherine Norman (USA), Andreas Scheba (Austria), Tetsuji Tanaka (Japan)

Review Editors
Habib Amamou (Tunisia), Edward Carr (USA)

Volunteer Chapter Scientist
Hauke Broecker (Germany)

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Executive Summary

Rural areas still account for almost half the world's population, about 75% of the developing world's poor people and 80% of the world's hungry. [9.1.1] There is a lack of clear definition of what constitutes rural areas, and definitions that do exist depend on definitions of the urban. [9.1.2] Across the world, the importance of peri-urban areas and new forms of rural-urban interactions are increasing. [9.1.3] However, rural areas, seen as a dynamic, spatial category remain important for assessing the impacts of climate change and the prospects of adaptation. [9.1.1] A lack of focus on rural areas in policy making increases their vulnerability to climate change. [9.2]

Climate change in rural areas will take place in the context of many important economic, social and land-use trends *(very high confidence)*. In different regions, rural populations have peaked or will peak in the next few decades. [9.3.1] The proportion of the rural population depending on agriculture is extremely varied across regions, but declining everywhere. Poverty rates in rural areas are falling more sharply than overall poverty rates, and proportions of the total poor accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising.

Rural people in developing countries are subject to multiple non-climate stressors, including under-investment in agriculture (though there are signs this is improving), problems with land policy, and processes of environmental degradation *(high to very high confidence)*. Hunger and malnutrition remain prevalent among rural children in South Asia and Sub-Saharan Africa. In developing countries,the levels and distribution of rural policies are affected in complex and interacting ways by processes of commercialisation and diversification, food policies, and policies on land tenure. In industrialized countries, there are important shifts towards multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors and a change from subsidy-based to investment-based policy. [9.3.1, Table 9-1]

Prevailing development constraints, such as low levels of educational attainment, environmental degradation and gender inequality create additional vulnerabilities to climate change [9.4.4] *(high confidence)*. There are low levels of agreement on some of the key factors associated with vulnerability or resilience in rural areas [9.3.5.2], including rainfed as opposed to irrigated agriculture [9.3.5.2.1], small-scale and family-managed farms [9.3.5.2.2], and integration into world markets. [9.3.5.2.4]. There is greater agreement on the importance for resilience of access to land and natural resources [9.3.5.2.5], flexible local institutions [9.3.5.2.6], and knowledge and information [9.3.5.2.7], and the association of gender inequalities with vulnerability. [9.3.5.2.9]. Specific livelihood niches such as pastoralism, mountain farming systems, and artisanal fisheries are vulnerable and at high risk of adverse impacts

(medium to high confidence), partly due to neglect, misunderstanding or inappropriate policy towards them on the part of governments.

Cases in the literature of observed impacts on rural areas often suffer from methodological problems of attribution, but evidence for observed impacts, both of extreme events and other categories, is increasing. [9.3.2] *(medium confidence).* Impacts attributable to climate change include declining yields of major crops, extreme events such as droughts and storms, and geographically-specific impacts such as glacier melt in the Andes.

Future impacts of climate change on the rural economic base and livelihoods, land-use and regional interconnections are at the latter stages of complex causal chains *(high confidence).* These flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. This increases the uncertainty associated with any particular projected impact. [9.3.3]

Major impacts of climate change in rural areas will be felt through impacts on water supply, food security [9.3.3.1] and agricultural incomes. [9.3.4.1] *(high confidence).* In certain countries shifts in agricultural production, of food and non-food crops, could take place. [9.3.3.1] Price rises, which may be induced by climate shocks apart from other factors [9.3.3.3.2], have a disproportionate impact on the welfare of the poor in rural areas, such as female headed households and those with limited access to modern agricultural inputs, infrastructure and education. [9.3.3.1]

Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security while affecting rural households depending on whether they are net-buyers or net-sellers of food. [9.3.3.3] (*medium to high confidence).* There is medium level agreement that deepening agricultural markets through trade reform and institutional efforts to improve the predictability and the reliability of the world trading system as well as by investing in additional supply capacity of small-scale farms in developing countries could help reduce market volatility and manage food supply shortages which might be caused by climate change [9.3.3.3.2]

Migration patterns will be driven by multiple factors of which climate change is only one [9.3.3.3.1] *(high confidence).*Given these multiple drivers of migration and the complex interactions which mediate migratory decision-making by individual or households, the detection of the effects of climate change on intra-rural and rural-to-urban migration remains a major challenge.

Climate policies, such as encouraging cultivation of biofuels, and payments under REDD, will have significant secondary impacts on land-use, and resulting negative impact on livelihoods, in some rural areas. [9.3.3.4] *(medium confidence).* These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance.

Most studies on valuation highlight that climate change impacts will be significant especially for the developing regions, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations. [9.3.4] *(high confidence).* Valuation of climate impacts needs to draw upon both monetary and non-monetary indicators. The valuation of non-marketed ecosystem services [9.3.4.6] and the limitations of economic valuation models which aggregate across multiple contexts [9.3.4] pose challenges for valuing impacts in rural areas.

There is a growing body of literature on successful adaptation in rural areas, including documentation of practical experience [9.4.3]. Gender, the supply of information for decision-making, and the role of social capital in building resilience, are all key issues. [9.4.1] Constraints to adaptation come from lack of access to credit, land, water, technology, markets and information; and are particularly pronounced in developing countries. [9.4.4] *(high confidence)*

9.1. Introduction

9.1.1. Rationale for the Chapter

Rural areas, even after significant demographic shifts, still account for 3.3 billion people or almost half (47.9%) of the world's total population (UN-DESA Population Division 2012). The proportion of people in developing countries living in rural areas is higher than the global average, with 71.5% of the population (or about 608 million people) living in rural areas in the least developed countries, and 50.3% of the population (or about 2.5 billion people) living in rural areas in other less developed countries (excluding LDCs), – compared to only 22.3% of the population (or about 276 million people) in more developed countries.

The overwhelming majority of the world's rural population (3.1 billion people, or 91.7% of the world's rural population, or 44.0% of the world's total population) live in rural areas in less developed or least developed countries. Rural dwellers also account for about 75% of the developing world's poor people (Ravaillon *et al.*, 2007) and 80% of the world's hungry (UNDP, 2005). At the same time, changes in land-use and livelihoods in rural areas make it less straightforward to link rural areas with agriculture or food production. Given the association of climate vulnerability with poverty and food insecurity, and the number of people living in rural areas in developing countries, these areas are significant sites for vulnerability to climate change. Much of the literature reviewed in this chapter therefore reflects these conditions, in which rural development issues (especially in developing countries) are closely intertwined with the physical impacts of climate change and the vulnerability of rural populations.

The Fourth Assessment Report (AR4) of the IPCC contains no specific chapter on "rural areas". Material on rural areas and rural people is found throughout the AR4, but rural areas are approached from specific viewpoints and through specific disciplines. Agriculture and food production, the impacts of which are assessed by Easterling *et al.* (2007), clearly take place mainly in rural areas, but that chapter was not able to cover impacts on other human activities taking place in rural areas or of significance to rural people. Many rural people follow livelihoods directly dependent on unmanaged or less-managed ecosystems, such as forests. However, the AR4 chapter on ecosystems (Fischlin *et al.*, 2007) was not able to cover the indirect impacts of ecosystem change on such livelihoods. The chapter on industry, settlement and society (Wilbanks *et al.*, 2007) reaches important conclusions about specific vulnerabilities of both urban and rural systems to climate change, but much of the literature reviewed and the most important conclusions, on high-density settlements, industry and infrastructure, are implicitly concerned with urban areas.

This chapter, under the general heading of "Human Settlements, Industry, and Infrastructure" assesses the impacts of climate change on, and the prospects for adaptation in, rural areas, seen as diverse patterns of settlement, infrastructure and livelihoods, in complex relations of interdependence with urban areas. Some of the key considerations will be as follows.

- Rural areas are largely defined in contradistinction to urban areas, but that distinction is increasingly seen as problematic.
- Rural areas are a spatial category, associated with certain patterns of human activity, but with those associations being subject to continuous change.
- Rural populations have, and will have, a variety of income sources and occupations, within which agriculture and the exploitation of natural resources have privileged but not necessarily predominant positions.
- Rural areas suffer from specific vulnerabilities to climate change, both through their dependence on natural resources and weather-dependent activities, and through their relative lack of access to information, decision-making, investment and services. Adaptation strategies will need to address these vulnerabilities.

The chapter will complement the treatment of issues also dealt with in Chapter 7 "Food Production Systems and Food Security" and Chapter 4 "Terrestrial and Inland Water Systems", but will primarily look at how biophysical impacts of climate change on agriculture and on less-managed ecosystems translate into impacts on human systems (and in this regard will complement sections of Chapter 12 "Human Security"). It will also address issues dealt with in Chapter 12 "Human Security" and Chapter 13 "Poverty and Livelihoods", but primarily from the point of view of

rural areas as spatial categories with particular characteristics. It will also draw out rural implications of climate change in different regions as covered in chapters 23-29.

9.1.2. Definitions of the Rural

"Rural" and "rural areas", in both policy-oriented and scholarly literature are terms often taken for granted or left undefined, in a process of definition that is often fraught with difficulties (IFAD 2010). Ultimately, however, in developing countries as well as developed countries, the rural is defined as the inverse or the residual of the urban (Lerner and Eakin, 2010). Human settlements in fact exist along a continuum from 'rural' to 'urban', with 'large villages', 'small towns' and 'small urban centres' not clearly fitting into one or the other. The populations of these ambiguous settlements tends to range from a few hundred to approximately 20,000 inhabitants, with 20 to 40 percent of the population in many nations living in settlements in this category (Satterthwaite, 2006). The variations in definitions from country-to-country can best be described through several examples (from both developed and developing countries of different sizes):

- In Australia, "major urban areas" are defined as having a population of 100,000 and over; while "other urban areas" have a population of 1,000 to 99,999. "Rural areas" included small towns with a population of 200 to 999. (Australian Bureau of Statistics n.d.).
- In India, urban areas are defined essentially as those with populations of 5,000 or more, or where at least 75% of the male working population is non-agricultural, or having a density of population of at least 400 people per km^2 (Government of India, 2012).
- In Jamaica, a place is considered to be urban if it has a population of more than 2,000 people and provides a certain set of amenities and facilities that are deemed to indicate "modern living" (Statistical Institute of Jamaica, 2012).
- In the United States, rural areas are defined by the Bureau of the Census as consisting of all territory outside of defined urbanized areas and urban clusters, that is open country and settlements with fewer than 2,500 residents. Such areas can in practice have population densities as high as 999 persons per square mile (386 persons/km^2) (Womach, 2005).

Definitions of the rural are therefore variable between countries, recognized as problematic, and subject to various attempts at refinement and sub-classification. While remaining aware of these issues, this chapter will in general assess literature on current trends in rural areas, and on climate impacts, adaptation and vulnerability, using whatever definitions of the rural are used in that literature.

9.1.3. Between 'Rural' and 'Urban': the Peri-Urban Interface

Authors have increasingly recognized that the simple dichotomy between 'rural' and 'urban' has "long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South" (Simon *et al.*, 2006:4). One approach to reconciling this is through the increasing application of the concept of "peri-urban areas" (Simon *et al.*, 2006; Simon, 2008). These areas can be seen as rural locations that have "become more urban in character" (Webster 2002: 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be "largely rural landscapes" (Learner and Eakin 2010: 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). A more elaborate conceptualization is offered by the Bahasa Indonesian term *desakota*, which is used in academic literature to incorporate arecognition of the diversified economic systems that exist across the urban-rural spectrum, and the closely interlinked, co-penetrating rural/urban livelihoods, communication, transport and economic systems (Desakota Study Team 2008; McGee 1991; Moench and Gyawali 2008).

Peri-urban or *desakota* systems therefore incorporate a change in the type of relationships between human society and ecosystems, and create shifts in the geographical and social distribution of risk and vulnerability (Pelling and Mustafa, 2010). The characteristics of these regions can both increase and decrease disaster and climate risk, and can pose both opportunities and challenges for disaster response and reconstruction (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of

livelihood options and improving access to education – but can also encourage land expropriation to enable commercial development (hence increasing vulnerability of those who are made landless). Similarly, the expansion of local labour markets and wage labour in these areas can strengthen adaptive capacity through providing new livelihood opportunities – but can simultaneously increase disaster risk as reliance on wage labour can increase dependence on the external economy and exposure to systemic shocks (Pelling and Mustafa, 2010: 7, Figure 2).

While there have been some assessments of "land degradation" and "sustainability" in peri-urban areas (e.g. Allen, 2006; Diaz-Chavez, 2006; Gough and Yankson, 2006; Binns and Maconachie, 2006), these have not yet focused on how these areas will be affected by climate change, or how the process of peri-urbanization will shape vulnerability or resilience. However, ecosystem services are particularly important in these areas, and environmental degradation – again, including the impacts of climate change (Desakota Study Team, 2008) – will influence ecosystems services and their role as a foundation for livelihood systems across developing countries in these systems, with particularly important consequences for the poor.

9.2. Findings of Recent Assessments

Table 9-1 summarises key findings on rural areas from AR4 (particularly Easterling *et al*., 2007 on agriculture, Wilbanks *et al*., 2007 on industry, settlement and society, and Klein *et al*. 2007 on links between adaptation and mitigation), and relevant findings from the International Assessment of Agricultural Knowledge, Science and Technology for Development (McIntyre, 2009). All these sources stress uncertainty, the importance of non-climate trends, complexity and context-specificity, in any findings on rural areas and climate change.

[INSERT TABLE 9-1 HERE
Table 9-1: Major findings of the IPCC Fourth Assessment Report and the International Assessment of Agricultural Science and Technology for Development.]

9.3. Assessing Impacts, Vulnerabilities, and Risks

9.3.1. Current and Future Economic, Social, and Land-Use Trends in Rural Areas

Climate change in rural areas will take place against the background of the trends in demography, economics and governance which are shaping those areas. While there are major points of contact between the important trends in developing and industrialized countries, and the analytical approaches used to discuss them, it is easier to discuss trends separately for the two groups of countries.In particular there is a close association in developing countries between rural areas and poverty. Table 9-2 summarizes and compares the most important trends across the two groups of countries. Figure 9-1, Table 9-3, and Figure 9-2 focus on two specific trends in developing countries: demographic trends and trends in poverty indicators.

[INSERT TABLE 9-2 HERE
Table 9-2: Major demographic, poverty-related, economic, governance, and environmental trends in rural areas of developed and developing countries.]

[INSERT FIGURE 9-1 HERE
Figure 9-1: Trends in rural (red), urban (purple), and total (green) populations by region. Solid lines represent observed values and dotted lines represent projections. Source: United Nations, Department of Economic and Social Affairs/Population Division (2012).]

[INSERT TABLE 9-3 HERE
Table 9-3: Poverty indicators for rural areas of developing countries.]

[INSERT FIGURE 9-2 HERE
Figure 9-2: Demographic and poverty indicators for rural areas of developing countries, by region. R: percentage of rural population; A/R: agriculture as percentage of rural; P: incidence of poverty; RP: incidence of rural poverty; EP: incidence of extreme poverty; ERP: incidence of extreme rural poverty; R/EP : rural as percentage of those in extreme poverty. Source: Adapted from IFAD (2011).]

9.3.2. Observed Impacts

Documentation of observed impacts of climate change on rural areas involves major questions of detection and attribution. Much discussion of vulnerability and adaptive capacity in rural areas, especially work based on qualitative fieldwork at community level, reports local perceptions of climate change, or uses local meteorological data without systematic attempts to distinguish between decadal trends and manifestations of anthropogenic climate change (see for example chapters in Ensor and Berger, 2009, and Castro *et al*., 2012). Similarly, impacts, vulnerability and adaptive capacity are frequently discussed in the context of extreme events, and perceived increases in their frequency, without systematic discussion of the difficulties of attributing extreme events to anthropogenic climate change (see Paavola, 2008 as an example). Exposure to non-climate trends and shocks further complicate the issue (Nielsen and Reenberg, 2010). Warner and van der Geest (submitted), use the UNFCC terminology of "loss and damage" for evidence of observed impacts of changes in monsoon patterns, drought, flooding, coastal erosion and saline intrusion on rural livelihoods in nine countries in Africa, Asia and the Pacific, but specify that the research methods employed do not allow attribution of climatic stressors to underlying causes such as anthropogenic climate change. Box 18-4 of this report discusses the considerable potential of using Traditional Ecological Knowledge to detect climate trends, but also the difficulties of using it to attribute trends to anthropogenic climate change. Implied equivalence between perceptions, local decadal trends and global change is not a problem in the context of detailed social-scientific analysis of vulnerability, adaptive capacity and their determinants, but becomes more problematic if such work is implied to be evidence for observed impact.

The impacts of climate change on patterns of settlement, livelihoods and incomes in rural areas will be the result of multi-step causal chains of impact. Typically, those chains will be of two sorts. One sort will involve extreme events, such as floods and storms, as they impact on rural infrastructure and cause direct loss of life. The other sort will involve impacts on agriculture or on ecosystems on which rural people depend. These impacts may themselves stem from extreme events, from changing patterns of extremes due to climate change, or from changes in mean conditions. The detection and attribution of extreme events is discussed by by the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC 2012, Seneviratne *et al.,* 2012). The detection and attribution of impacts on ecosystems and on agriculture are dealt with in Chapters 4 and 7 of this report. Both exercises are complex.

Seneviratne *et al*. (2012) give a detailed and critical assessment of the detection and attribution of observed patterns of extreme events, which shows greatly varying levels of confidence in the attribution to climate change of global and regional trends. For example they state that it is *likely* there has been a worldwide increase in extreme high-water events during the late 20th century, and it is *likely* that there has been an anthropogenic influence on this. They have *medium confidence* in detecting trends towards more intense and frequent droughts in some parts of the world (Southern Europe and West Africa) since 1950. They note that opposite trends exist elsewhere, and that there is *low confidence* in any trend in drought in, for example, East Africa, although other authors, such as Lyon and DeWitt (2012) see a "recent and abrupt decline in the East African long rains" since 1999. Seneviratne *et al*. (2012) assign *low confidence* to any observed long-term increases in tropical cyclone activity, or attribution of any changes in cyclone activity to anthropogenic influence. They state that "attribution of single extreme events to anthropogenic climate change is challenging" (2012:112).

Handmer *et al*., (2012) discuss both observed and projected impacts of extreme events on human systems and ecosystems. Numerous examples are given of observed impacts of extreme events – especially heatwaves, droughts and floods – on water, ecosystems, and agriculture (particularly smallscale farming), though these are not explicitly attributed to climate change. The impacts of droughts on African agriculture in recent decades are noted. Significant impacts on settlement, infrastructure and tourism are discussed, though the major focus is on urban areas.

Important categories of extreme events causing negative impacts in rural areas include tropical storms and droughts: Hurricane Stan in October 2005 affected nearly 600,000 people on the Chiapas coast as a consequence of flooding and sudden river overflows (Saldaña-Zorrilla, 2008). Droughts produce severe economic distress in rural areas. Employment reduction as a consequence of lower agricultural productivity and ultimate migration are two of the most common responses (Gray and Muller, 2012). Ericksen *et al*. (2012) review a variety of livestock mortality rates, up to 80% of livestock in some areas, for recent droughts in the Horn of Africa

Climate change impacts on agriculture and ecosystems run through rising temperature and changes in rainfall variability and seasonality as well as through extreme events. Lobell *et al*. (2011) adopt a different approach to and scale of analysis by examining global yields of the four major agricultural commodities, from 1980 to 2008, in relation to temperature trends and in relation to a counterfactual without climate trends. Yields of maize and wheat declined by 3.8 and 5.5% respectively relative to the counterfactual, which offset in some countries some of the gains from improved agricultural technology. Badjeck *et al*. (2010) discuss current and future impacts on fisherfolk across the world. Many local-level studies are subject to the attribution problems mentioned above, but Wellard *et al*. (2012) cautiously note a convergence of climate data with the perceptions of farmers and officials to the effect that over the last 30 years the rainfall in Malawi has become less predictable, that the rainy season is arriving later in the year causing delays in planting of the main crops, and that damaging dry spells during the rainy season have become more likely.

Glacial retreat in Latin America is one of the best evidenced current impacts on rural areas. In highland Peru there have been rapid observed declines since 1962 in glacier area and dry-season stream flow, on which local livelihoods depend, which accord well with local perceptions of changes that are necessitating adaptation (Orlove, 2009). Other studies of the area focus both on observed changes in water availability and on glacial lake outburst floods, which are attributable to climate change (Bury *et al*., 2009; Carey, 2010, Carey *et al*. 2012). There is also a rich specialized literature on the impacts of shrinking sea-ice and changing seasonal patterns of ice formation and melt on Inuit in circumpolar regions (Ford, 2009; Beaumier and Ford, 2010).

Migration associated with weather-related extremes or longer-term climate trends is discussed in Chapter 12, Table 12-3, with empirical examples of migrations linked to droughts, coastal storms, floods and sea level rise. Attribution of migration to climate change is extremely complex, as recognized by Black *et al*. (2011). Life in rural areas across the world typically involves complex patterns of rural-urban and rural-rural migration, which are modified or exacerbated by climate events and trends rather than solely caused by them. Black *et al*. (2011) see environmental drivers of migration as operating in combination with economic, political, social and demographic drivers. MacLeman and Hunter (2010), argue that analogies of historical migration trends associated with environmental change though not with global climate processes, such as the 1930s Dustbowl in the USA (Reuveny (2007) allow closer examination of such multiple causality.

9.3.3. Future Impacts

This section will examine the major impacts of climate change identified or projected for rural areas, under the headings of: economic base and livelihoods; landscape and regional interconnections, including migration, trade, investment and knowledge; and second-order impacts of climate policy. The following section, 9.3.4, assesses literature on impact through a different and specific lens, that of economic valuation, though there is some overlap. The biophysical impacts of climate change on food crops are dealt with primarily in Chapter 7; but also here and in section 9.3.4 insofar as they affect rural economies. Biophysical impacts on non-food cash crops, in particular beverage crops, are discussed below.

As with the observed impacts in section 9.3.2, the future impacts of climate change described here, and quantified in section 9.3.4, are at the latter stages of complex causal chains that flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. This increases the uncertainty associated with any particular impact on the economic base, on land-use or on regional interconnections.

Some of the discussion here will involve issues of vulnerability, particularly contextual vulnerability, but this is discussed more fully in section 9.4 below.

9.3.3.1. Economic Base and Livelihoods

Climate change will affect rural livelihoods, or "the capabilities, assets (stores, resources, claims and access) and activities required for a means of living" (Chambers and Conway, 1992).This is because many rural livelihoods are dependent on natural resources (e.g. agriculture, fishing and forestry), and their availability will vary in a changing climate. This may have effects on human security and wellbeing (Kumssa and Jones, 2010).

The livelihoods framework allows analysis of livelihoods outcomes as embedded within an external context of multiple stresses and dynamics, all of which change over time (Kepe, 2008). Climate variability and change interacts with, and sometimes compounds, existing livelihood pressures in rural areas, such as economic policy, globalization, environmental degradation and HIV/AIDS, as has been shown in Tanzania (Hamisi *et al*., 2012), Ghana (Westerhoff and Smit, 2009), South Africa (O'Brien *et al*., 2009; Ziervogel and Taylor, 2008; Reid and Vogel, 2006), Malawi (Casale *et al*., 2010), Kenya, (Oluoko-Odingoa, 2011), Senegal (Mbow *et al*., 2008) and India (O'Brien *et al*., 2004).

Especially for agriculture and other traditional livelihoods in developing countries, the concept of the "centrality of the social" (Fairhead and Leach, 2006) is important: social relations within households (particularly gender relations) and between households, profoundly affect production decisions, management of knowledge, and marketing (Morton, 2007). Similarly access to diversification as an adaptation to climate extremes depends on gender, age, governance and institutions, as shown in studies in South Africa, Tanzania and Uganda (Goulden *et al*., 2009).

Morton (2007), adapting findings from AR4, suggests that the impacts of climate change on smallholder and subsistence farmers can be conceptualized as a combination of: biological processes affecting crops and animals at organism or field level; environmental and physical processes affecting production at a landscape, watershed or community level; and other impacts, including those on human health and on non-agricultural livelihoods. This schema is developed by Anderson *et al*. (2010), with a cross-cutting dimension of extreme events, increased variability and shifts in average temperature and rainfall, as well as introducing indirect impacts, for example through trade and food prices, and through climate mitigation policies.

An additional dimension is effects of climate change on water supply which in turn affect rural livelihood bases, whether through a decrease or increase. In South Africa, for example, most of the climate change models predict a reduction in freshwater availability by 2050, and a computable general equilibrium approach shows that this will adversely affect household welfare (Juana *et al*., 2008). In the Mount Kenya region, in contrast, the NRM3 Streamflow Model under the TGICA climate change projection will result in an increase of annual runoff by 26%, with a severe increase in flood flows, and a reduction of the lowest flows to about a tenth of the current value (Notter *et al*., 2007). Changing rainfall levels will also affect groundwater levels, which play a role in rural livelihoods. At the continental level in Africa, analysis of existing rainfall and recharge studies suggests that climate change will not lead to widespread catastrophic failure of improved rural groundwater supplies (Macdonald *et al*., 2009). However, at higher resolution groundwater resources are threatened (e.g. in South Africa, Knüppe, 2011), and water crises are expected to multiple resulting from the increasing demand, and this will further affect the people in rural areas who fetch water (Nkem *et al*., 2011).

Water availability plays a key role in the viability of agricultural livelihoods, alongside changes in temperature. Climate change is expected to impact water resources in the Asian region in a major way. A study by the World Bank (2010a) argues that diminishing Himalayan glaciers would impact the agricultural water supply and food security of more than one billion people in Asia. There are some regional and country studies, which support this view. Likewise, Immerzeel *et al*. (2010) in a study of major river basins of the region viz. Indus, Ganges, Brahmaputra, Yangtze and Yellow rivers conclude that different river basins would experience different impacts on water availability and food security due to climate change. They further argue that the Brahmaputra and Indus basins

would be more susceptible to changes in water availability affecting the food security of 60 million people (ibid). ADB (2009a) argues that climate change would increase water stress in four south East Asian countries of Indonesia, Philippines, Thailand and Vietnam.

In assessing the impacts of climate change on water resources in rural areas of Europe, it is predicted that Mediterranean climates will experience more pressure on water resources from reduced rainfall and meltwater from glacial ice and snow. Schroter *et al*. (2005) predict that in the Mediterranean region summer water supply could fall by 20 to 30% following global warming of 2ºC and 40 -50% for 4ºC . These declines would increase the costs of production and living in the South (Falloon and Betts, 2010). Drought could threaten biodiversity and traditional ecosystems particularly in Southern Europe with problems exacerbated by declining water quality. Decline in economic activity may increase rural depopulation and harm the development of rural communities in Southern Europe (Westhoek *et al*., 2006). Given the rapid population growth, economic development and hence increasing completion over water resources (for both agricultural and non-agricultural uses) in the Middle East, the per capita availability of water will be reduced significantly for rural populations (see also Chapter 22) (Chenoweth J, *et al*., 2011; Rochdane *et al*., 2012; Iglesias *et al*., 2010; Hanafi *et al*., 2011, Sowers *et al*., 2011; Verner, 2012: 166). According to MacDonald *et al*. (2009) climate change will not lead to a widespread failure of improved rural groundwater supply in Africa, but it could affect a population of up to 90 million people, as they live in rural areas where annual rainfall is between 200 and 500mm per year, and where decreases in annual rainfall, changes in intensity or seasonal variations may cause problems for groundwater supply.

Various studies conclude a decline in crop yield of agriculture due to climate change over the next three to four decades in different parts of the world (Section 7.2.1, Chapter 7, AR5). For the Asia –Pacific region several studies have concentrated on impacts emanating from the agricultural sector (ADB & IFPRI, 2009; ADB, 2009a; Srivastava *et al*., 2010; De Silva *et al*., 2007; Xiong *et al*., 2009, 2010; Ramirez-Villegas *et al*., 2011) *S*imilarly, studies on the adverse impacts of climatic changes on yields in different parts of North America, Australia and Europe have been conducted (Warren *et al*., 2006; Olesena *et al*., 2011; Anwar *et al*., 2007; COPA COGECA, 2003; Schlenker and Roberts, 2009; Roberts and Schlenker, 2010; Niemi *et al*. 2009; Wolfe *et al*. 2008). The impacts of climate change on the smallholder and rain-fed dominated (96% of all agricultural land is rain-fed) agricultural sector are considered to be very significant to the economies and livelihoods in Africa (Müller *et al*., 2011; Kotir, 2011; Collier *et al*., 2008; Hassan, 2010). These results emerge across a range of scenarios. Several other studies also map declines in net revenues from crops and the associated links with food security and poverty (Molua, 2009; Thurlow *et al*., 2009; Reid *et al*., 2008; World Bank, 2010a; Thurlow and Wobst, 2003. Yield patterns are expected to present spatial differences in South America, as projected by various studies with some losing such as bean growers in Central America and some gaining such as sugarcane cultivators in Brazil. Such country case studies are based on climate projections for SRES A2 and B2 scenarios derived by Hadley Center HadRM3P model (Pinto and Assad, 2008; ECLAC, 2009; ECLAC, 2010a). Adverse impacts on yield derived on the basis of simulations of the above mentioned scenarios imply that since bean growers in Central America are small, low-income farmers, climate change may have large repercussion throughout the region, endangering the food security of large segments of the population (ECLAC, 2010b).

There will also be impacts on non-food cash crops, (or industrial crops), which represent an important source of livelihood in many rural areas. However they have received less attention than traditional agricultural crops when assessing the impacts of climate change. Relevant crops include cotton and other fibres, wine grapes, beverage crops, and a wide variety of others. Yields of several cash crops in the Middle East such as olives, apples and pistachios may decline if winter temperatures are too high (Verner, 2012). Literature on biofuels such as jatropha focuses on the impacts of biofuels on climate change rather than on the effects of climate on yields and other relevant variables in these agricultural systems. Where crops have dual use as food and biofuel (for example oilseeds, sugarcane, sugar beet, maize and wheat) impacts can be inferred from studies that focus on their use for food.

The findings of Easterling *et al*., (2007), that cotton yields are likely to decrease as changes in temperature and precipitation overcome potential benefits of increasing carbon dioxide have been corroborated in other studies, where yield reductions have been estimated the order of 10% (Lee *et al*., 2001) causing substantial economic losses. It is reported that the cotton cultivation in Israel will declined by 52% and 38% under the A2 and B2 scenarios, and

that the net revenue will also decrease by 240% and 173% in the scenarios (Haim *et al*., 2008: 433). Few systematic assessments have been done on other fibre crops such as jute, kenaf, and flax.

Climate change impacts on wine grapes have been extensively studied and documented. Climate impacts such as increasing number of hot days and decreasing frost risk may benefit some varieties. Lobell *et al*. (2006) assess the impacts of climate change on yields of six perennial crops in California by 2099. This paper presents that the production of wine grapes will experience relatively small changes compared to other commodities during the concerned period. The uncertainty analysis shows the yield variations are limited within 10% although Gatto et al. (2009) argue that the revenue of the industry in Napa, California could declined by 2034. Jones *et al*. (2005) indicate that future climate change will exceed climatic thresholds affecting ripening for existing varieties grown at the margins of their climatic limits. Warmer conditions could also lead to more poleward locations potentially becoming more conducive to grape growing and wine production.

The case of tropical beverage crops, in particular coffee, is discussed in Box 9-1, and projected changes in area suitable for all three tropical beverage crops are set out in Table 9-4.

____ START BOX 9-1 HERE ____

Box 9-1. Impacts of Climate Change on Tropical Beverage Crops

The major traded beverage crops coffee, tea and cocoa support the livelihoods of several million small-scale producers in over 60 countries of the tropics of Africa, Asia and Latin America. Coffee production has long been recognized as sensitive to climate variability with global production and prices sensitive to occasional frosts in Brazil – the world's largest producer. Likewise the livelihoods of millions of small producers are dependent both on stability of production and stability in world prices. During the last crash in coffee prices from 2000-2003 poverty levels in the coffee growing regions of Nicaragua increased, while they fell in the rest of the country (World Bank, 2003); subsequently during the drought associated with El Nino in 2005 coffee productivity fell to between a third and half of normal similarly leading to severely reduced income for small producers (Haggar, 2009).

Analysis of the effects of recent climate change on coffee producing areas in Mexico by Gay *et al*. (2006) show that in Veracruz between 1969 and 1998 rainfall has decreased by 40mm and temperatures have increased by 0.02ºC per year. They developed econometric models of the relationship between coffee productivity and fluctuations in temperature and precipitation, which gave an R-squared of 0.69 against historical data. Extrapolating the historical tendencies in temperature and precipitation to 2020 and applying their econometric model they predict that coffee production could decline by 34%, but most importantly this decline in production takes producers from making net profits of on average around US$200 per acre, to less than $20 per acre. This has led to a series of studies projecting the effects of climate change on the distribution of Arabica coffee growing areas of the coming decades summarized below.

For Brazil, Pinto *et al*., (2004) have mapped the changes in area suitable for coffee production in the four main coffee producing states. A 3ºC increase in temperature and 15% increase in rainfall (taken from the general prediction of climate change for Southern Brazil in the IPCC 2001 report) would lead to major changes in the distribution of coffee producing zones. In the main coffee producing states of Minas Gerais and Sao Paulo the potential area for production would decline from 70-75% of the state to 20-25%, production in Gioas would be eliminated, but only a 10% reduction in area in Parana. New areas suitable for production in Santa Catarina and Rio Grande do Sul will only partially compensate the loss of area in other states (Pinto and Assad, 2008). The economic impacts of a rise in temperature of 3ºC would cause a 60% decline coffee production in the state of Sao Paulo equal to nearly 300 million dollars income (Pinto *et al*., 2007).

Models developed by CIAT predict the distribution of coffee under the A2a climate scenario using a statistical downscaling of the climate change data from 20 different GCM models used in the IPCC Fourth Assessment. They use WorldClim data to characterize the current distribution of coffee using 19 climatic variables and then use the climate data downscaled to 1, 5 and 10 km resolution to map where those conditions may occur in the future (2020 or 2050). This method has been applied to coffee distribution in Kenya (CIAT 2010), Central America and Mexico

(Laderach *et al*., 2010), tea production in Kenya (CIAT, 2011b) and Uganda (CIAT, 2011b), and cocoa production in Ghana and Ivory Coast (CIAT, 2011c) (Table 9-4). Only one similar study appears to have been done for Robusta coffee (Simonett, 2002) in Uganda, which appears to show similarly drastic changes in both distribution and total area suitable for coffee production. At a minimum climate change will cause considerable changes in the distribution of these crops disrupting the livelihoods of millions of small-holder producers, in many cases the total area suitable for production would decrease considerably with increases of temperature of only 2-2.5ºC. Although some local areas may have improved conditions for coffee production, e.g. high altitude areas of Guatemala, the overall predictions are for a reduction in area suitable for coffee production by 2050 in all countries studied.

____ END BOX 9-1 HERE ____

[INSERT TABLE 9-4 HERE
Table 9-4: Projected changes in areas suitable for production of tropical beverage crops by 2050.]

Food security, which is also discussed in Chapters 7 and 13, is now known to reflect a broader range of factors than merely food production (Sen, 1992). In three countries in Africa – Ethiopia, Malawi and Niger - mass mortality food crises since 2000 -were triggered by a moderate decline in crop and/or livestock production, exacerbated by "exchange entitlement failures" – food price spikes and asset price collapses (Devereux, 2009).). For example, the food crisis of 2007-2008 exposed the vulnerability of rural livelihoods to external price shocks. Review of the evidence shows that price rises have a disproportionate impact on the welfare of the poorest of the poor in rural areas - female-headed households (which tend to be poorer than male-headed households) and those who have limited access to land, modern agricultural inputs, infrastructure and education (Ruel *et al*., 2009: 3). This has illustrated that the vulnerability of rural livelihoods is affected by not only ecological, but also social and economic factors that mediate or hinder people's access to different assets and capacities to adapt (Ericksen, 2008a, b; Ellis, 2000: 290-91). However, changes in production will play a role in affecting food security and resultant increases in malnutrition (Ringler, 2010).

Post-harvest aspects of agriculture – storage on farm and commercially, handling and transport – have been relatively neglected in discussions of climate change, but will be affected by changes in temperature, rainfall, humidity, and by extreme events. Many adaptation opportunities are already understood by postharvest service providers, but getting postharvest knowledge into use at scale is a significant challenge (Stathers *et al*. submitted).

Rural food security is discussed extensively in the regional chapters of this report. Major themes include: for Africa the range of contributing factors including globalization (22.3.3.1.5), and the adaptation responses of farmers (22.3.3.16); for Asia (24.4.4) the regional variation in yields across crops and countries, and potential for adaptation; for North America the high food insecurity in Mexico and the vulnerability to climate change of food security in indigenous communities (26.6, 26.7); for Central and South America (27.3.4) the threats to the food security of the poor in specific agricultural regions, and the inter-linkages between food and bioenenergy and farmers' responses. Links between food security and agriculture trade are also discussed in 9.3.3.3 below.

Agricultural livelihoods are not restricted to crops, but also involve livestock in a variety of farming systems (Devendra *et al*. 2005). Thornton *et al*. (2009) view the impacts on livestock of climate change as a neglected research area, complicated by other drivers of change, broader development trends, rapid change in livestock systems, spatial heterogeneity and social inequality between livestock-keepers. Drawing on livestock science, range ecology and projected climate trends, they review some possible future impacts through quantity and quality of feeds, heat stress, water, disease and others. Impacts through drought will be significant, as will heat stress, particularly of *Bos taurus* cattle. Impacts through animal health and disease will be even harder to predict than other categories of impact (Thornton *et al*., 2009). Aggregating at the level of one country, Kabubo-Mariara (2009) shows that livestock production in Kenya is highly sensitive to climate change, whereby increased mean precipitation of 1% could reduce revenues by 6%.

Pastoralists, who are dependent on livestock grazed in arid, semi-arid or mountainous areas, represent a specific case, display very specific combinations of adaptive capacity, especially through mobility, and vulnerability, as discussed in 9.3.5 below. Ericksen *et al*. (2012), with particular reference to East Africa, discuss possibilities of loss

of rangeland productivity, changes in rangeland composition towards browse species, and changes in herd dynamics through more frequent droughts as possible impacts. In the Middle East, rangelands will be under substantial climate stress which may reduce their carrying capacity, in light of the growing demand for meat products and the region's growing size livestock population (Verner, 2012: 166). Little *et al*. (2001) discuss impacts of floods, directly and through disease, on pastoral herds. Six SRES scenarios generated by six GCMs were used by Hein *et al* .(2009) for the Ferlo Region in Northern Senegal, where livestock keeping is the main economic activity of the rural population. A modest reduction in rainfall of 15% in combination with a 20% increase in rainfall variability could have considerable effects on livestock stocking density and profits, reducing the optimal stocking density by 30%.

As extensive livestock production is associated with semi-arid areas marginal for cropping, some authors project shifts toward livestock production under climate change. Jones and Thornton (2009) identify major transition zones across Africa where increased probability of drought between now and 2050 will create conditions for shifts from cropping to livestock. Data from over 9000 African livestock farmers in 10 countries shows that farmers are more likely to have livestock as temperatures increase and as precipitation decreases, based on logit analysis to estimate whether farmers adopt livestock, followed by three econometric models to determine species choice. These analyses predict a decrease in the probability of beef cattle and an increase in the probability of sheep and goats, and more heat-tolerant animals will dominate the future in Africa (Seo and Mendelsohn, 2007a). A development of the Ricardian method shows that these choices relate to the net income of different animal species. On this basis, large-scale commercial beef cattle farmers are most vulnerable to climate change in Africa, particularly since they are less likely to have diversified (Seo and Mendelsohn, 2007b). To Sallu *et al*. (2010), investment in and accumulation of physical assets, including land and livestock, can be a strategy to decrease vulnerability

Livelihoods dependent on fisheries will also experience vulnerability to climate change. Impacts of climate change on aquatic ecosystems will have adverse consequences for the world's 36 million fisherfolk as well as the nearly 1.5 billion consumers who rely on fish for more than 20% of their dietary animal protein (Badjeck *et al*., 2010). An indicator approach showed that economies with the highest vulnerability of capture fisheries to climate change were in Central and Western Africa (e.g. Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in north-western South America, and four tropical Asian countries (Bangladesh, Cambodia, Pakistan, and Yemen)(Allison *et al*., 2009). This vulnerability arises from the combined effect of predicted climate change on fish stocks, the relatively high share of fisheries as a source of income (including export earnings) and diets, and limited societal capacity to adapt due to the prominence of poverty in these societies (Allison *et al*., 2009). In another study of changes in climate and social systems in north eastern Asia on fisheries development, Kim (2010) argues that in countries like China, Japan and South Korea these changes could have a negative impact on fisheries adversely affecting livelihoods and food security of the region. (Chapter 7, AR5, provides an assessment of the impacts of climate change on the biological and ecological processes in aquatic ecosystems and on livelihoods that depend on the fisheries and aquaculture sector).

Diversification into non-farm incomes might accelerate if climate-related risks of farm income failure increase as a result of climate change, although it is also determined by other factors such as poverty, income distribution, farm output, gender, labour and credit markets (Ellis, 2000). Such diversification would help households achieve low risk correlations between their livelihood components (Ellis, 2000).

9.3.3.2. Infrastructure

Assessments of the impacts of climate change on infrastructure take a general or urban perspective and do not focus on rural areas, though rural impacts can be inferred. For example, river flooding and sea level rise will produce temporary loss of land and land activities, and transportation infrastructure particularly on coastal areas (Kirshen et al 2008). Climate change will affect current water management practices and the operation of existing water infrastructures, which are very likely to be inadequate to overcome the negative impacts of climate change on water supply reliability (Kundzewicz *et al*., 2008). Some documented impacts on dams, reservoirs and irrigation infrastructure are: reduction of sediment load due to reductions in flows (associated with lower precipitation), this positively affects infrastructure operation (Wang *et al*., 2007); impacts of climate variability and change on storage capacity that creates further vulnerability (Lane *et al*., 1999); and failures in the reliability of water allocation

systems (based on water use rights) due to reductions of streamflows under future climate scenarios (Meza *et al.*, 2012).

9.3.3.3. Spatial and Regional Interconnections

In both developing and developed countries, rural areas have been increasingly integrated with the rest of world. The main channels through which this rapid integration process takes place are migration (permanent and cyclical), commuting, transfer of public and private remittances, regional and international trade, inflow of investment and diffusion of knowledge through new information and communication technologies (IFAD, 2010), as well as the spatial intermingling of rural and urban economic activities, labelled as desakota systems and discussed in Section 9.1.3 above. A trend to increase in urban areas can be associated with different spatial patterns, reflecting alternative development processes, e.g. periurbanisation versus counter-urbanisation (Rounsevell *et al.*, 2007). In this context, changes in the occurrence of some types of extreme events due to climate change, increased variability, and changing mean climate parameters are *likely* to have significant implications for regional and global integration trends in rural areas.

9.3.3.3.1. Migration

Growing efforts are researching environmental migration, building on the AR4 conclusion that extreme events might lead to changed patterns of migration (Boko *et al.*, 2007). Though the impacts of climate change are *likely* to affect population distribution and mobility, it is difficult to establish a causal relationship between environmental degradation and migration, which is still termed "complex and unpredictable" (Brown, 2008). Hence, the link between internal migration and environmental stresses is contested. One school of thought shows migration (and particularly rural out-migration) increasing during times of environmental stresses (e.g. Afifi, 2011; Gray and Mueller, 2012), with projections that these trends will continue under climate change (Kniveton et al, 2011). This may also affect human security (Brown and Crawford, 2008). Growing vulnerability to environmental change may also lead to an increase in abandonment of settlements (McLeman, 2011).

However, some estimates and forecasts of the potential number of displaced people because of climate change are being challenged by another body of literature which argues that migration rates are no higher under conditions of environmental or climate stress (Black, 2011; van der Geest, 2011; van der Geest and de Jeu, 2008; Tacoli, 2009; McLeman and Hunter, 2010; Gemenne, 2011; Foresight, 2011; Cohen, 2004; Brown, IOM, 2008). Some studies have ascertained (Mertz *et al.,* 2007; Parnell and Walawege, 2011) that climatic variabiity is certainly one of the most significant catalyst for migration toward urban areas, as has been the case during the severe droughts occurred in the Sahel in the 70s and the 90s, but the current alarmist predictions of massive flows of refugees (so called ''environmental refugees'' or ''environmental migrants''), are not supported by past experiences of responses to droughts and extreme weather events and predictions for future migration flows are tentative at best (C. Tacoli, 2009; M'bow 2011). Similarly, a recent survey by Mertz *et al.* (2010) has argued that climate factors play a limited role in past adaptation options of sahelian farmers.

There have also been attempts to understand the nexus between migration and climate change through examining analogous experiences in the past and present in which climate variability is associated with particular kinds of population movements (McLeman and Hunter 2010). For example, in Ghana the causality of migration was established to be relatively clear in the case of sudden-onset environmental perturbations such as floods, whereas in case of slow-onset environmental deterioration, there was usually a set of overlapping causes - political and socioeconomic factors – which come into play (van der Geest, 2011). Given the multiple drivers of migration (Black *et al.*, 2011) and the complex interactions which mediate migratory decision-making by individual or households (Raleigh, 2008; McLeman and Smit, 2006; Kniveton and Al., 2011, Blake and Al, 2011), the detection of the effects of climate change on intra-rural and rural-to-urban migration remains a major challenge.

9.3.3.3.2. Trade

Although agricultural exports accounted for only one sixth of world agricultural production and consumption (Anderson, 2010), it is the sector for which most data is available, and is the focus here. Between 2000 and 2008, the value of global agricultural exports rose from US$ 551 billion to US$ 1,342 billion, representing an average annual growth of 5 percent (WTO, 2009). In addition to trade in primary crops, trade in processed food, fish and forest products has also been expanding (WTO, 2009). However, the fundamentals of agricultural trade have changed significantly in the late 2000s. There was a major agricultural price spike, and historically high degree of price volatility towards the end of the period. Some cyclical and structural factors – such as droughts in several major producers, including Australia, Ukraine and the United States, creating shortage of cereals in international markets, the expansion of bio-fuels at the expense of food crop production, export controls, growing demand by emerging economies for secondary agricultural products such as meat, energy and feed crops, financial speculation – have led to a volatile and unpredictable trading environment (FAO, 2008; Timmer, 2010; Schmidhuber and Matuschke, 2010; Karapinar and Haberli, 2010; Headey , 2011).

Against this backdrop, climate change is expected to affect the pattern and volume of international agricultural trade flows. At the sectoral and product levels, it may alter the comparative advantage of countries and regions through its potential impacts on their agricultural supply capacities. These effects will be reflected on agricultural prices – which are the signals of economic scarcity or abundance. Recent studies produce even more pessimistic projections of climate change on food prices differentiated at the crop level than did AR4 (Easterling *et al.,* 2007). For example, simulations results of two climate models —the National Centre for Atmospheric Research, US (NCAR) and the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO) —based on A2 scenario inputs — suggested that climate change might result in additional price increases in 2050, ranging from 30-37 percent for rice, 52-55 percent for maize to 94-111 percent for wheat (Nelson *et al*., 2009). If CO_2 fertilization is taken into account, the 2050 price increases are expected to be smaller (for example, by 15-17 percent for rice relative to no CO_2 fertilization). It is important to note that these price increases are projected in addition to the price increases (62 percent in rice, 63 percent maize, and 40 percent in wheat) that are expected under no-climate-change scenario, which are largely driven by population and income growth projected to be greater than productivity and area growth (Nelson *et al*., 2009a). Other studies, using different models and scenario combinations, produce significantly different results in relation to price projections. For example, IFPRI using the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) estimates additional price increases for 2050 (relative to no-climate change) of 32- 34 percent for maize (with baseline and pessimistic scenarios in relation to population and income growth (e.g. human well-being)), 18-20 percent for rice (with optimistic and pessimistic human well-being scenarios) and 23-24 percent for wheat (with baseline and pessimistic human well-being scenarios) (Rosegrant, *et al.,* 2008; Nelson *et al*., 2010). This reflects the high level of uncertainty on price predictions (Rivera-Ferre and Ortega-Cerdà, 2011) and the caution needed to develop food policies.

The prices of beef, pork and poultry are also projected to increase significantly under A2 inputs simulated in CSIRO and NCAR models. Accordingly, in addition to the projected price increases, under no-climate-change scenario, of 33%, 36%, 35% for beef, pork and poultry respectively, 20%, 18%, 21% increases are projected for 2050 under climate change scenario for these three commodities respectively, without taking into account CO2 fertilization ((Nelson *et al*., 2009a).

The projected production and price changes across regions will affect trade flows substantially. Without climate change, net developed-country exports (of rice, wheat, maize, millet, sorghum, and other grains) to developing countries are expected to increase by 22.4 million mt, from 83.4 million mt to 105.8 million mt between 2000 and 2050, representing a growth of 27 percent (Nelson *et al*., 2009b). Climate change might lead to an additional export volume of 0.9 million mt (with wetter NCAR scenario) to 39.9 million mt (with drier CSIRO scenario) (Nelson *et al*., 2009b). Developed-country exports are projected to increase by an additional 12 to 18 percent relative to no climate change if CO2 fertilization is taken into account (Nelson *et al*., 2009b). Regions such as South Asia, East Asia and Pacific are projected to increase their imports substantially over this period. For example, South Asia which exported around 15 million mt in 2000 is expected to import up to 54 million mt (with drier CSIRO scenario) (Nelson *et al*., 2009b). By 2050, the Middle East and North Africa region and Sub-Saharan Africa which are already net importers of cereals are estimated to increase the volumes of cereals imports by 29 and 30 percent, respectively

(Nelson *et al*., 2009b). In addition, due to climate impacts on prices, trade flow values will increase even at higher rates than trade volumes.

However, there are other models producing substantially different projections for developed country cereals exports. For example, MIROC scenario (produced by the Center for Climate System Research, University of Tokyo) with A1B-induced production effects on U.S. maize production project a radical decline in net maize exports by up to 70 percent by 2050 (Nelson *et al*., 2010). This is in sharp contrast to the projection that U.S. exports would double under no-climate change scenario (Nelson *et al*., 2010). These different projections underline the high degree of uncertainty in the climate scenarios.

The literature highlights the potential role of international trade in managing the effects of climate change on agricultural productivity (Nelson *et al*., 2009; Huang *et al*., 2011:12; Jankowska, et al 2012). Models show that world trade volumes would need to increase substantially to offset the negative welfare effects of climate-change induced crop yield variability (Reimer and Li, 2009). This would also allow some countries to capitalize on new export opportunities arising from higher achievable yields, for example in Argentina (Asseng *et al*., 2013) or increasing heterogeneity of climate impacts on yields, for example in Tanzania (Ahmed *et al*., 2012). Similarly, it is projected that climate-induced food deficits occurring in low income developing countries will be supplied, fully or partly through food aid. Hence food aid agencies, which have already been struggling to deliver aid in an environment of growing scale of poverty and malnutrition due to the recent price hikes and of historical volatility in food aid supplies might face additional operational challenges (Barrett and Maxwell, 2006; Harvey *et al*., 2010). Staple food trade might also save water resources, and hence contribute to adaptation efforts in rural areas, as the total volume of embedded water ("virtual water") in trade is projected to decrease under climate change (Konar *et al.,* 2013).

The potential role that trade could play in managing the impacts of climate change will inevitably be affected by countries' trade policies. For example, during the 'food crisis' of 2007–2008, dozens of countries instituted various forms of export restrictions on food staples, in order to maintain domestic availability of supplies, which created additional volatility in global markets (Anderson and Nelgen, 2012; Headey, 2011; Karapinar, 2011, 2012). Low-income countries are particularly vulnerable to such volatilities (FAO, 2008; Reimer and Li, 2009).
The emerging literature on the subjects illustrates that deepening agricultural markets through trade reform, improved market access, and institutional efforts to improve the predictability and the reliability of the world trading system as well as by investing in additional supply capacity of small-scale farms in developing countries could help reduce market volatility and offset supply shortages which might be caused by climate change (UNEP, 2009; WTO, 2009; Nelson *et al*., 2009a and 2009b; Reimer and Li, 2009; Ahmed *et al*., 2012).

9.3.3.3.3. Investment

Climate change may also affect investment patterns in rural areas. On the one hand, countries, regions and sectors that are expected to be affected adversely by climate change may have difficulty attracting investment. On the other hand, ecological zones that will become favourable due to climate change are expected to see increasing inflow of investment. For example the recent price hikes in agricultural commodities have led to new initiatives of foreign direct investment (FDI) in the form of large-scale crop production in poor countries (Anseeuw *et al*., 2012; World Bank, 2010). This type of FDI seems to follow a new pattern whereby capital-endowed countries with high imports of food or feed crops are preparing to invest in large production projects in low-income countries endowed with low-cost labour force, land and water resources. Climate change may lead to similar investment patterns. However, there is a risk that these new investments might not be integrated into local structures and the local populations becoming increasingly vulnerable as they might lose access to vital assets such as land and water (Anseeuw *et al*., 2012). On the other hand, if FDI comes with a basket of new technology, business connections, infrastructure and human capital, and if such investments lead to local business development and employment generation, they could bring substantial benefits to the host country (World Bank, 2010).

9.3.3.3.4. Knowledge

Rural areas, as never before, are exposed to diffusion of knowledge through migration, trade and investment flows, technology transfers, and improved communication and transport facilities (IFAD, 2010), although differentials n knowledge access between rural and urban areas remain. Future impacts of climate change on these channels of integration will affect the pace and intensity of knowledge transfers. For example, increased transport and communication connectivity can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education (Pelling and Mustafa 2010). If trade, migration and investment flows will be intensified as a result of climate change, this will inevitably have a positive impact on knowledge transfer both from and to rural areas.

Traditional Ecological Knowledge (TEK and also known by a variety of other terms), developed to adapt to past climate variability and change, can both be impacted by climate change and used and transformed in adaptation (Nyong, *et al.,* 2007). Ettenger (2012) discusses how seasonal hunting camps among the Cree of Northern Quebec that were the occasion for intergenerational knowledge transfer have been disrupted by changing bird migrations, while new technologies such as the internet, GPS and satellite phones have been integrated into livelihood strategies. Climate-change induced migration can threaten LTK transfer (Valdivia *et al*., 2010; Giles *et al*., 2013). Disaster management by cental government may undermine decentralization efforts, disfavouring TEK transfer (Dekens, 2008).

9.3.3.4. Second-Order Impacts of Climate Policy

Policy responses to climate change impact on rural people and can affect their livelihoods and environment. The need to work towards increasing energy supply from renewable resources as responses to climate change, will in time manifest themselves in landscape changes, whether it be through the granting of planning consents for wind farms, the creation of a market for energy crops, structural changes in coastal defences, etc. (Dockerty *et al*., 2006), or increased employment opportunities (del Río and Burguillo, 2008).

Social responses to these changes are expected (Molnar 2010) while some impacts have already been documented. One of the most analysed is the promotion of biofuel crops, which have been an extremely controversial issue in the last decade. Delucchi (2010) concludes that biofuels produced from conventional intensive agriculture will exacerbate stresses on water supplies, water quality, and land use, and thus will have impacts on rural areas (land-use change) and agriculture. Concerns have already been expressed about the impact of biofuel production on food security due to increase in food prices, increasing land concentration (and landgrabs), and competition for water (Eide, 2008; Müller *et al*., 2008). Gurgel *et al*. (2007) modeled potential production and implications of a global biofuels industry: estimated production at the end of the century will reach 220-270 exajoules in a reference scenario, and 320-370 exajoules under a global effort to mitigate greenhouse gas emissions. They recognise the need for a high land conversion rate to achieve this. Delucchi (2010) suggests developing biofuels programs with low inputs of fossil fuels and chemicals, that do not require irrigation, and that use land with little or no economic or ecological value in alternative uses (Plevin *et al*., 2010). This implies analysing each case in its context, including production for both local and global markets.

Another relevant climate-policy developed in the last few years under the UNFCCC umbrella has been the REDD mechanisms. Major criticisms of this instrument arise from the difficulties posed for the participation of communities in REDD programs and its potential in undermining a general decentralization of forest management (Phelps, Webb, and Agrawal 2010), which is shown to be essential for a sustainable management of forests and reducing vulnerability of forest-dependent communities. Campbell (2009) notes the presence of some ssynergies between mitigation through REDD and adaptation, but also trade-offs between REDD, rural incomes, and rural equity. To address these problems Sikor *et al*., (2010) suggest the recognition and operationalizing of forest peoples' rights through participation of communities in decision-making, equitable distribution of forest benefits, and recognition of their particular identities. This will require the implementation of a polycentric approach implying a nested forest and climate governance.

9.3.4. Valuation of Climate Impacts

This section assesses literature on climate change impacts through studies that have adopted various economic methods for valuation of impact. Valuation of impacts of climate change on rural areas is a difficult task and should reflect the significance of the ecological service categories for different stakeholders, including women (Kennet 2009) and minority groups, and ideally the valuations of unit changes in the levels of those services across management options. Valuations can be made at individualistic or communal levels (Farber *et al*., 2006). different understandings of value may exist (Spangenberg and Settele, 2010; Kosoy and Corbera, 2010), as well as different philosophical approaches to address it (from positivists to ethicists) (Weisbach and Sunstein, 2008), which makes more difficult to agree on valuation methodologies. The impacts of climate change are expected to be unequally distributed across the globe, with developing countries at a disadvantage, given their geographical position, low adaptive capacities (Stern, 2007; World Bank, 2010a) and the significance of agriculture and natural resources to the economies and people (World Bank, 2010b; Collier *et al*., 2008). Both direct and indirect impacts have been projected, such as lower agricultural productivity, increase in prices for major crops and rise in poverty (Hertel *et al.,*2010), which have implications for rural areas and rural communities. This section discusses literature on the valuation of impacts as relevant for rural areas and arising from climate change, with reference to agriculture, fisheries and livestock, water resources, GDP and rural economy, extreme weather events and sea level rise and health. There are various channels through which changes in economic values may occur in rural areas, such as through changes in profitability, crop and land values and loss of livelihoods of specific communities through changes in fisheries and tourism values. Losses and gains in health status and nutrition, and wider economy-wide impacts such as changes in job availability and urbanization also impact economic values that accrue to rural communities, the opportunities and the constraints that rural communities experience and changes that rural landscapes undergo. The impact on availability of fresh water resources is another major area of concern for the developing regions in particular. Climate change can adversely impact poverty through multiple channels (Section 10.9, chapter 10, AR5).

Viewing impacts regionally, despite the ongoing debates around the uncertainty and limitations of valuation studies, scholars generally agree that African countries could experience relatively high losses compared to countries in other regions (World Bank, 2010b; Watkiss *et al*., 2010; Collier *et al.,* 2008). These conclusions emerge across a range of climate scenarios and models used by researchers. For instance, Watkiss *et al*. (2010) use the FUND model for a business as usual scenario and a mitigation 450ppm 2 degrees scenario as generated by using the PAGE2002 model, while the World Bank uses a range of country specific models for calculating costs. Overall negative consequences are seen for Africa and Asia, due to changes in rainfall patterns and increases in temperature (Müller *et al*., 2011). Though climate change and climate variability would impact a range of sectors, water and agriculture are expected to be the two most sensitive to climatic changes in Asia (Cruz *et al*., 2007, Chapter 3 AR5) and for droughts in particular for Australia (Nelson *et al.,* 2007, Meinke and Stone 2005). In South American countries, higher temperatures and changes in precipitation patterns associated with climate change affect the process of land degradation, compromising extensive agricultural areas in LAC countries. Research on climate change impacts in rural North America has largely focused on the effects on agricultural production and on indigenous population, many of whom rely directly on natural resources. Developed countries in Europe will be less affected than the developing world (Tol *et al.,* 2004), with most of the climate sensitive sectors located in rural areas.

Valuation and costing of climate impacts, draws upon both monetary and non-monetary metrics. Most studies use models that estimate aggregated costs or benefits from impacts to entire economies, or to a few sectors, expressed in relation to a country's gross domestic product (GDP) (Stage, 2010; Watkiss, 2011). Values which are aggregated across sectors generalise across multiple contexts and could mask particular circumstances that could be significant to specific locations, while expressing outcomes in aggregated GDP terms. This is a matter of concern for economies in Africa and Asia, where subsistence production continues to play a key role in rural livelihoods. Valuation of non marketed ecosystem services poses further methodological and empirical concerns (Dasgupta, 2008; Dasgupta *et.al*., 2009; Watkiss, 2011; Stage, 2010). Würtenberger *et al*. (2006) developed a methodology to estimate environmental and socio-economic impacts of agricultural trade regarding virtual land use, and Adger *et al*. (2011) use qualitative methodologies to consider non-market and non-instrumental metrics of risk, based on

principles of justice and recognition of individual and community identity, which they suggest should be considered in decision-making.

Integrated assessment models and cost-benefit tools have been criticised for not being a valid tool to assess intergenerational events, processes with high levels of uncertainty and irreversibility, for not considering equity concerns, power structures, or for assigning monetary values on the basis of incomplete information or assuming speculative judgments regarding the monetary value of, e.g. natural resources (Ackerman et al. 2009; Toman 2006; Kuik *et al*., 2008), not recognising incommensurability (Aldred 2012). In recent years, various perspectives for valuing the economic impacts of climate change have come into focus including the feminist (Nelson 2008; Power 2009), deliberative (Zografos and Howarth 2010) or behavioural economics (Brekke and Johansson-Stenman 2008; Gowdy 2008), and the integration of economics with moral and political philosophy (Dietz *et al*., 2008). Some common characteristics of these new approaches include transdisciplinarity, acknowledging the diversity of views and maintaining complexity in models. Research in this area although relatively recent, shows promise.

Illustrative regional and sub-regional estimates for the value of impacts of climate change are presented here. Estimates for agriculture in most cases relate directly to rural lives. A range of other impacts on which available information exists is also considered, since these values and costs concern significant proportions of livelihoods and assets in rural areas. It is also to be noted that available literature concentrates on certain sectors and a few countries. For instance, research on specific rural populations is less developed than for particular sectors that are largely located in rural spaces such as agriculture. Limited information is available on West Asia and Pacific islands, on health impacts for both Africa and Asia, small and poor communities of the Arctic (Furgal and Seguin 2006, Furgal and Prowse, 2008; Ford and Pearce, 2010).

9.3.4.1. Agriculture

Changes in agricultural production will have corresponding impacts on incomes and wellbeing of rural peoples. The largest known economic impact of climate change is upon agriculture because of the size and sensitivity of the sector, particularly in the developing world and to a lesser extent in parts of the developed world. A large number of studies to evaluate the impacts on the agricultural sector and its ramifications for communities have been conducted at various scales, ranging from micro level farm models to large scale regional and country level climate cum socio-economic scenario modeling exercises. Some of these also report values for associated economic losses. Since models are simplifications of complex real world phenomena, different models tend to highlight different aspects of impacts and their consequent economic values. For instance, in estimating economic losses the Ricardian method has been used widely to study climate change impacts in agriculture and inbuilt adaptation. However, often such analysis does not incorporate features like technological progress, relative price changes, agricultural policy and other dynamic characteristics. Similarly on the bio-physical impacts side, changes in the El Niño/Southern Oscillation (ENSO) statistics may also have serious economic implications for the agricultural sector in certain countries such as in Latin America and Australia (Kokic *et al.,* 2007). However, ENSO responses differ strongly across climate models, and at the current stage of understanding do not allow conclusions to be drawn on how global warming will affect the Tropical Pacific climate system (Latif and Keenlyside, 2009). A sample of the available studies is provided in Table 9-5.

[INSERT TABLE 9-5 HERE
Table 9-5: Illustrative sample of studies on economic value and changes in value from climate change.]

9.3.4.2. Other Rural Sectors: Water, Fisheries, Livestock, Mining

The changes in valuation of water resources due to climate change arise from expected impacts on populations dependent on these water resources and these will be felt in several parts of the world (Sections 3.4.9, 3.5 and 3.8, Chapter 3, AR5). Monetary estimates of losses due to impacts on water resources are not generalizable. Among alternative approaches to value water resources, use of the water footprint tool (Hoekstra and Mekonnen, 2012) and

the concept of virtual water has been suggested for informing policy-makers in water-scarce countries, such as Egypt.

Analysis of intergenerational valuation has shown to provide some interesting results in valuation of marine fisheries (Ainsworth and Sumaila 2005). For fisheries in rural coastal areas, some of the challenges faced include the valuation of environmental externalities such as breeding habitats, or mangroves, that might be lost due to climate change or other forces (Hall 2011). It has also been argued that the true worth of livelihoods dependent on fisheries in developing countries, where these constitute part of a diversified livelihood or subsistence strategy, requires a different set of metrics from those used in the developed world (Mills et al. 2011). Climate change can also have significant impacts on livestock keeping (Section 9.3.3.1 current chapter). Franco *et al*. (2011) reveal significant declines in forage for ranching in California under SRES scenarios B1 and A2. The dairy sector in California is predicted to lose $287-902 million annually to climate impacts by the end of the century (Lal *et al.,* 2011).

A relatively less researched area which may impact the livelihoods of rural communities is mining (Section 26.11.1.2). Pearce *et al*. (2011) highlight the current and ongoing vulnerability of mining and mining communities in Canada, often rural and with few other economic activities, to climate change. Current and past infrastructure for mines was built under a no-climate change presumption and economic and ecological vulnerabilities as a result are substantial, and industry actors are unprepared to deal with this. As with other industrial sectors, the extent of loss would vary depending on the importance of the sector in the local economy (Backus *et al*., 2012).

9.3.4.3. GDP and Economy-Wide Impacts

In a regional review of economics of climate change in four south East Asian countries of Indonesia, Philippines, Thailand and Vietnam, ADB suggests that climate change would result in a mean annual loss of 2.2% of GDP by 2100 if only market related impact is accounted. If non market impacts related to health and ecosystems are also accounted for, then it would result in 5.7% annual loss of GDP for the same period (ADB, 2009a). Bigano *et al*. (2008) suggest that a predicted 25cm rise in sea level alone would result in a GDP loss of 0.1% in southeast Asia by 2050. Another estimate suggests that four Asian countries of Bangladesh, India, Philippines and Vietnam had a cumulative loss of $20billion due to natural disasters in the last decade, which makes them quite sensitive to climate risks (ADB, 2009 b). In case of Bangladesh, which is extremely vulnerable to climate change because of a large area less than 5 metres above sea level, a single severe cyclone could result in damages worth $9 billion by 2050 accounting for 0.6% of the country's GDP (ADB, 2009b). Most of the impacted regions are rural, and coastal. Thus the implied losses in GDP become relevant for the rural communities in these countries.

Coastal and island rural communities throughout North America are less able to afford major infrastructure improvements and will thus be more vulnerable to the effects of sea level rise, including waterborne and food borne diseases, water table salinity, and diminished storm protection from affected reefs and wetlands, but detailed costs are very site-specific (Hess *et al.,* 2008). Cordalis *et al*. (2007) discuss the climate vulnerabilities and policy complexities facing Native American tribes and note that moving villages where needed could cost billions of dollars.

In Arctic Canada and Alaska, infrastructure built for very cold weather will deteriorate as the air and ground warm. Larsen *et al*. (2008) estimate increases in public infrastructure costs of 10-20 percent through 2030 and 10% through 2080 for Alaska, amounting to several billion dollars, much of it to be spent outside of urban centers. The climate models used were part of the IPCC's coordinated AOGCM model inter-comparison project and the underlying model assumptions are based on a middle-of-the-road ''A1B'' emissions and growth scenario defined by the IPCC. Lemmen *et al*. (2007) reports that foundation fixes alone in the largely rural Northwest Territories could cost up to CAN$420 million, and that nearly all of Northern Canada's extensive winter road network, which supplies rural communities and supports extractive industries which bring billions of dollars to the Canadian economy annually, is at risk. Replacing it with all-weather roadways is estimated to cost CAN$85,000/km.

9.3.4.4. Extreme Weather Events, Sea-Level Rise

The climate change related extreme events that may cause changes in economic values in rural areas include heat waves and droughts, storms, inundation and flooding (Stern 2007; Handmer *et al*., 2012; Section 3.4.9, Chapter 3, AR5). A detailed discussion on the costs of climate extremes and disasters is set out by Handmer *et al*., 2012. Costs can be of two kinds: losses or damage costs and costs of adaptation. While some of the costs lend themselves to monetary valuation (such as infrastructure costs) others cannot be easily estimated such as the value of lives lost and the value of eco system services lost (for discussion on the methodologies for valuing costs refer to Handmer *et al*., 2012: Section 4.5.3).

Damage costs of floods and droughts (Section 10.3.1, chapter 10, AR5) and from rise in water levels in Europe (Swiss Re, 2009a) demonstrate the cost implications for rural communities in the developed regions of the world. Studies mapping the adverse impacts in UK and Europe show a range of sectors that are impacted in rural areas particularly due to drought in Europe and flooding in UK. For instance, major impacts hit farming and forestry with an estimated $15 billion production lost through drought, heat stress and fire (Munich Re 2004), the worst effect being on summer crops in Mediterranean regions (Giannakoupoulos *et al*., 2009). Longer term adaptation could reduce the severity of losses but could include displacement of agricultural and forestry production from Southern Europe to the North. The UK Government's Foresight Programme (2004) estimates that global warming of 3 to 4 ºC could increase flood damage from 0.1% up to 0.4% of GDP. In Europe costs could rise from $10 billion today to $120-150 billion by 2100. With strengthened flood defences these costs may only double. Much of the investment in flood defences and coastal protection would be in rural coastal areas.

Several studies from the developing countries provide evidence on the substantial costs rural communities in particular face in these countries. Salinity and salt water intrusion have implications for rural livelihoods as they impact both fisheries and agriculture (Section 5.5.3, Chapter 5, AR5). Sea level rise also leads to wetland loss and coastal erosion. A few illustrations of the range of impacts of relevance for the rural economy are provided here. Loss of agricultural land and changes in the saline-freshwater interface is estimated to impact the economies of Africa adversely (SEI, 2009, S. Dasgupta *et al.,* 2007). Ahmed *et al*., (2009) suggest that climate volatility from increase in extreme events, increases poverty in developing countries, particularly Bangladesh, Mexico, Indonesia and in Africa. They also find that on simulating the effect of climate extremes on poverty in Mexico using the SRES A2 scenario as generated by CMIP3 multi-model dataset, rural poverty increases by 43-52% following a single climate shock. Kronik and Verner (2010) note that some 12% of Mexico's population is indigenous and that these rural subsistence communities are vulnerable to extreme weather events and often depend on climate-sensitive crops like coffee. Studying extreme events Boyd and Ibarrarán (2009) use a CGE model to simulate the effects of a long drought on the Mexican economy and find declines in production of 10-20% across a variety of agricultural sectors. Scenario-based stakeholder engagement has been tested for coastal management planning under climate change threats (Tompkins *et al*., 2008) and to determine impacts and responses of extreme-events in coastal areas (Toth and Hizsnyik, 2008).

9.3.4.5. Recreation and Tourism; Forestry

Studies assessing the changes in economic value of recreation and tourism due to climate change are relatively fewer in number (coastal tourism is discussed in Section 5.4.4.2, Chapter 5, AR5). While some studies locate an increase in values for certain regions others estimate shifts in tourism and losses (Bigano *et al*., 2007; Hamilton *et al*., 2005; Beniston, 2010), methodological challenges and contrasting findings for the short and long run pose problems in generalizing findings (economic values for recreation and tourism are discussed in Section 10.6, Chapter 10, AR5). Change in economic values will impact rural communities (Lal *et al*., 2011), with the linkages between biodiversity, tourism and rural livelihoods and rural landscapes being an established one both for developing and developed countries (Nyaupane and Poulde 2011, Scott *et al*., 2007, Hein *et al*., 2009).

It has been argued that climate change would have adverse impacts on various ecosystems, including forests and biodiversity in many regions of the world (AR4; Stern, 2007; Eliasch, 2008; Ogawa-Onishi *et al.,* 2010; ADB, 2009a; Tran *et al.,* 2010; Preston *et al*., 2006) and these will have implications for rural livelihoods and economies

(Chopra and Dasgupta, 2008; Safranyik and Wilson, 2006; Kurz *et al*., 2008; Walton, 2010). However, monetary valuation of changes in non-marketed ecosystem services due to climate change continue to pose a challenge to researchers. To overcome some of the limitations, multicriteria analysis has been used for forest management (Fürstenau *et al*., 2007).

9.3.4.6. Health

Some studies have looked at the health impacts in various regions of the world, however for the most part these do not by and large distinguish the rural from the urban sector . Studies have examined the linkages between health and climate change in terms of the implications for vector-borne and waterborne diseases for Asia and Africa. No comprehensive assessment of climate change effects on health in Africa or Asia has been conducted so far, and there remain considerable gaps in knowledge (Costello *et al*., 2009; Byass, 2009). In general it appears that the region of Africa could be seriously affected if counter measures are not put in place (Byass, 2009; Costello *et al*., 2009; Ebi, 2008; SEI, 2009) and that most climate change related health impacts are in children of rural areas in Sub-Saharan Africa and Asia. As there is a lack of studies which consider rural areas specifically, the interested reader is referred to chapter 11 for current sources of vulnerability (Section 11.3.1, Chapter 11, AR5) and major climate sensitive health outcomes (section 11.2, Chapter 11, AR5). A discussion on the additional costs of treatment due to climate related health outcomes is available in Section 10.8.2, chapter 10, AR5. For region specific health concerns from climate change, the reader is referred to the following sections: North America (26.8, chapter 26); Central and South America (27.3.7, chapter 27); Small islands (29.3.3, chapter 29); Australia (25.6.9, Chapter 25); Asia (24.4.6, chapter 24); Europe (23.5.1 and 23.5.2, Chapter 23); Africa (22.3.3.2, chapter 22).

9.3.5. Key Vulnerabilities and Risks

9.3.5.1. Competing Definitions of Vulnerability

Discussions on climate vulnerability in rural areas is necessarily related to discussion on competing conceptualizations and terminologies of vulnerability, much of which arises from research based on case-studies located in rural areas. Different conceptualizations are important, because the policy prescriptions for rural areas derived from each are different (O'Brien *et al.,* 2007), or even contradictory. Two main concepts of vulnerability exist (O'Brien *et al.,* 2007; R. Nelson *et al.,* 2010; Füssel, 2007):

- Vulnerability viewed as a combination of exposure to hazards, sensitivity and adaptive capacity, as used in the Fourth Assessment Report of the IPCC, also called end-point or outcome vulnerability. The resulting policy options derived strongly emphasise new technologies as options to reduce vulnerability and enhance adaptive capacity. One important consequence of this is a downplaying of factors such as gender (V. Nelson *et al.,* 2002) or the status of indigenous people (O'Brien *et al*., 2009).
- Vulnerability viewed as arising from pre-existing socio-economic factors that make populations vulnerable to extreme events (or climate change), also called starting-point or contextual vulnerability, emphasizing climate change interactions with multiple processes of change and thus widening the It is assumed that vulnerability arises less from physical sensitivities of the resource base that supports the human system than from the social, economic and political facts that affect how the human system interacts with the resource base. The resulting policy options have a strong focus on diversity and local knowledge (Brondizio and Moran, 2008). This type of assessment has grown in the last few years.

In line with these interpretations different methodologies exist to measure vulnerability (inductive and deductive methods (Nelson *et al*., 2010); vulnerability variable, unicriterial or econometric assessment, e.g. centered on examining changes in agricultural yield, and vulnerability indicator or multicriterial approach. Recent discussions in this field also relate to whether studies should be centered on the analysis of vulnerability or resilience. Vulnerability implies a key role for targeted international development assistance in helping the rural poor while resilience research emphasises more bottom-up forms of assistance that allow adaptive capacities and flexible governance structures, and considers that conventional development assistance can exacerbate vulnerability before and after shocks (McSweeney and Coomes, 2011a). Cannon and Muller-Mahn (2010) however, suggest that resilience as a

focus is overly associated with the natural sciences while important social issues can be left behind in the assessments.

9.3.5.2. Drivers of Vulnerability and Risk

In this chapter we use vulnerability as a starting point, in which different trends can be observed in different situations, while we consider risk to be the product of impact, exposure and vulnerability. The most commonly used approaches to analyzing causes of vulnerability, use the concepts of entitlements or livelihoods in evaluating the multi-scale factors shaping people's assets. The importance and impact of drivers affecting vulnerability are seen as context and scale-dependent, although vulnerability is experienced locally, its causes and solutions occur at different social, geographic, and temporal scales (Ribot, 2010). Vulnerability in rural areas can be aggravated by non-climate factors which can operate at both individual and community levels (Eakin and Wehbe, 2009), and include the following:

- Physical geography, e.g. desert or semi-desert conditions (Lioubimtseva and Henebry, 2009), remoteness (Horton *et al*., 2010), level of dependence on climate conditions (Brondizio and Moran 2008))
- Economic constraints and poverty (Ahmed *et al*., 2011; Macdonald *et al*., 2009; Mertz, Halsnæs *et al*., 2009; Mertz, Mbow *et al*., 2009)
- Gender inequalities (V. Nelson *et al*., 2002)
- Social, economic and institutional shocks and trends (e.g. urbanization, industrialization, prevalence of female-headed households, landlessness, short-time policy horizons, low literacy, high share of agriculture in GDP), as well as demographic changes, HIV/AIDS, access and availability of food, density of social networks, memories of past climate variations, knowledge and long-term residence in the region (Macdonald *et al*., 2009; Mougou *et al*., 2011; Ruel *et al*., 2010; Sallu *et al.,* 2010; Simelton *et al.,* 2009; Mertz, Halsnæs *et al*., 2009; Parks and Roberts, 2006; Gbetibouo *et al*., 2010; Ahmed *et al.,* 2011; Cooper *et al*., 2008; Brondizio and Moran, 2008).

The adoption of different approaches in the analyses can result in contradictory findings regarding vulnerability in rural areas. Further, vulnerability being highly context-dependent, there are low levels of agreement on the direction in which some key factors may affect vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, integration into world markets, or poverty. For instance, poverty has traditionally been considered a clear factor increasing vulnerability to climate change, but McSweeney and Coomes (2011a) found that climate-related disasters can change the structural factors, fostering local capacities for endogenous institutional changes that enhance community resilience, intergenerational equity and long-term ecological sustainability. Brouwer *et al*. (2007) contrary to expectations found that vulnerability to flooding in Bangladesh in terms of damage suffered was lower for households that fully depended on natural resources than those who did not fully depend on natural resources. Also Osbahr *et al*. (2008) found that diversification in rural areas does not always reduce vulnerability and can increase inequity within communities if it is not accompanied by reciprocity.

There is greater agreement on the importance for resilience of drivers such as access to land and natural resources, flexible local institutions and knowledge and information, and the association of gender inequalities with vulnerability. This section focuses on the following drivers of vulnerability to climate change: water, market orientation, institutions, access to resources, gender, migration and access to information and knowledge.

9.3.5.2.1. Acces to water

Access to drinking and irrigation water is considered an important factor driving vulnerability to climate change of rural populations. Availability of water is also linked to other indicators such as income, agricultural employment and nutritional status in the household (Halsnæs and Trærup, 2009). Reducing vulnerability requires a reduction of the multiple non-climate-related pressures on freshwater resources (e.g. water pollution, high water withdrawals) together with improvement of water supply and sanitation in developing countries (Kundzewicz *et al*., 2008). It is agreed that water supply will be adversely affected by climate change, but vulnerability of populations will also be

determined by other elements, such as the role of institutions in facilitating the access to water, or people's demand, which in turn is influenced by local cultural norms (Wutich *et al*., 2012) and perceptions of vulnerability which may differ between men and women Larson, Ibes,and White 2011. Improvements in technologies can reduce the perception of water scarcity and increase water demand without reductions in underlying vulnerability (El-Sadek, 2010; Sowers *et al*., 2011). Where appropriate water management institutions exist and are effective, their role in improving rural livelihoods has been demonstrated, for example in Tanzania's Great Ruaha basin (Kashaigili *et al*., 2009).

Past research has tended to agree that rain-fed agriculture is more vulnerable to climate change (Bellon *et al*., 2011) and that irrigation is needed to decrease that vulnerability (Gbetibouo *et al*., 2010). More recent findings suggest that this is context-dependent and irrigation has been found to increase vulnerability in certain cases (Lioubimtseva and Henebry, 2009; Eakin, 2005). Cooper *et al*. (2008) concluded that in rainfed Sub-Saharan Africa the focus should be on improving productivity of rain-fed agriculture instead of irrigation as irrigation schemes are also being threatened by drought, and Ahmed *et al*. (2011) emphasised the role of drought-tolerant crops. It is important, both for rain-fen and irrigated agriculture, to promote water harvesting strategies, including storage and conservation.

9.3.5.2.2. Market orientation

Some authors argue that opening markets to international trade increases vulnerability of small farmers and poor people. However, linkages among international, regional and local markets are not clear, including how global prices affect regional and local prices in the long term (Ulimwengu *et al*., 2009). Market integration reduces the capacity of indigenous systems for dealing with climate risk in Bolivia (Valdivia *et al*., 2010) and Mozambique (Eriksen and Silva, 2009), and in the Sahel favours a shift towards cash-cropping a narrow range of commodities that increased dryland degradation (Fraser *et al*., 2011) as in Honduras (McSweeney and Coomes, 2011a), by accelerating socioeconomic stratification or focusing incomes in a single crop. Ruel *et al*. (2010) suggest that excessive dependence on cash income increases vulnerability of the urban poor compared with the rural poor, who can have access to other type of assets. According to Brooks *et al*. (2009) the dominant development paradigm favouring transitions from tradition to modernization, economic growth and globalization, does not favour action under uncertainty. They suggest the need for new models of development built *around* environmental constraints and opportunities which search for a balance between productivity and resilience.

On the other hand, Jones and Thorton (2009) estimated that rainfed mixed crop/livestock areas in sub-Saharan Africa which are far from large markets have higher poverty rates and thus, conclude they are more vulnerable to climate change. Also Gbetibou *et al*. (2010) proposed increased market participation as a valid measure to reduce vulnerability of vulnerable regions in South Africa as calculated by a vulnerability index. Thus, each case needs to be analysed within its complexity considering interactions among all factors that can affect vulnerability, to avoid magic recipes which can work in one place but not in other (Rivera-Ferre *et al*., submitted).

Regarding the scale of farms, some authors suggest that high reliance on small-scale farming increases the vulnerability of communities in rural areas (Bellon *et al*., 2011; Gbetibouo *et al*., 2010) although it is suggested that their resilience capacity (stemming from factors such as indigenous knowledge, family labour, livelihood diversification) should not be underestimated. On the contrary, Brondizio and Moran (2008) indicate that small farmers are less vulnerable than large, monocropp farmers when climatic variations make an area inappropriate for a particular crop, because they tend to cultivate multiple crops. However, they recognize that small farmers tend to suffer from technological limitations, low access to extension services, and market disadvantages. Mertz *et al*. (2009) suggest that history demonstrates small farmers are highly resilient as they face numerous changes and that the value of local knowledge in climate change studies has received little attention. For Eakin (2005), the shift in support to agriculture from subsistence to commercial agriculture in Mexico reduced smallholders resilience for climatic variations.

9.3.5.2.3. Institutions, access to resources, and governance

Vulnerability and livelihood security are closely linked to the institutional environment. Institutions and their networks can increase (Eakin, 2005) or reduce vulnerability to climate change. For that reason it is important to foster research on the role of local institutions in influencing vulnerability (Agrawal and Perrin 2008; Berman *et al.*, 2012). According to Agrawal and Perrin (2008) local institutions (as organizations) influence livelihoods in three manners: through distribution of risks related to climate hazards they can structure how particular social groups will be affected by them; they determine the incentive structures for household and community level adaptation responses; and they mediate external interventions (e.g. finances, knowledge and information, skills training) into local contexts, and articulate between local and extra-local social and political processes through which adaptation efforts unfold. In that manner, rural institutions structure risk and sensitivity in the face of climate hazards by enabling or disabling individual and collective action (Ribot, 2010). Governance structures and communication flows are important, as shown in a Swiss mountain region vulnerable to climate change (Ingold *et al.*, 2010). The knowledge and perceptions of decision-makers are important. Romsdahl *et al.*(2013) show that local government decision-makers in the US Great Plains resist seeing climate change as within their responsibilities, which has contributed to low levels of planning for either adaptation or mitigation, and thus to greater vulnerability, but that a reframing of issues around current resource management priorities could allow proactive planning.

According to Leach *et al.* (1999) institutions (as the rules of the game in society) mediate vulnerability by shaping access to resources as composed by endowments, entitlements and capabilities of different social actors. Anderson *et al.* (2010) associate flexible local institutions in dryland societies, primarily for resource management, with resilience to climate change and vulnerability reduction. Lack of access to assets, among which land is an important one, is accepted to be an important factor increasing vulnerability in rural people (McSweeney and Coomes, 2011a). The breakdown of traditional land tenure systems increases vulnerability (Fraser *et al.*, 2011; Dougill *et al.*, 2010) in many different ways. Lack of access to land is a multi-causal process, among which climatic change is just but one. For instance, Dougill *et al.* (2010) shows that land privatization in Bostwana has increased vulnerability of poorer communal pastoralist, although it has helped the wealthier farmers, remaining a route to enhance resilience as this private land-owning group has become less vulnerable. Brouwer *et al.* (2007) found that individuals with less access to natural productive resources are more vulnerable to flooding, being even higher when disparities of distribution at the community level are also higher. Lack of access to productive land is also linked to migration and conflicts. Obioha (2008) shows how reduction of access to productive land due to climatic changes increases communal civil violent conflicts in Nigeria.

9.3.5.2.4. Migration

The relationship of vulnerability to migration is complex. Vulnerable people can migrate, both as a coping and as an adaptive strategy, depending on the temporal scale of that migration. Areas of out-migration can experience reduced vulnerability if migrants send remittances, or increased vulnerability if the burden of work, usually for women, also increases. Social networks, essential to reduce vulnerability, are also affected reducing the transmission of traditional knowledge (Valdivia *et al.*, 2010). Furthermore, those places receiving migrants can experience an excessive demographic growth, which increases pressure over scarce resources, as it is being experienced in the semiarid tropics (Cooper *et al.*, 2008) or Africa (Obioha, 2008). Brondizio and Moran (2008) found that in-migration in the Amazon brought people with knowledge that is ill-adapted to the local environment.

9.3.5.2.5. Gender

Gender was a “latecomer” to the climate debate (Denton, 2004), but patterns of vulnerability reflects gender-related inequalities, of special relevance to rural areas in the developing world (Denton, 2002; Vincent *et al.,* 2010; V. Nelson and Stathers, 2009). Gender differences in roles, responsibilities and capabilities mean that climate change may actually reinforce disparities between men and women (Vincent *et al.*, 2010), in crucial key dimensions for coping with climate-related change, including inequalities in access to wealth, new technologies, education,

information, and other resources such as land. The major issues concerning gender and climate change in rural areas, not only in terms of vulnerability but also of enabling adaptation, are reviewed in Box 9-2.

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Box 9-2. Gender and Climate Change in Rural Areas

Differences in access to resources between men and women can create gender inequalities, which in turn leads to differential vulnerabilities and capacities to adapt (Nelson *et al*., 2002; Adger, 2006; O'Brien *et al*., 2007). Whilst recognised in AR4 (Adger *et al*., 2007) and SREX (IPCC, 2012), evidence since then has become stronger, with additional case studies on the gendered dimensions of climate change (e.g. Nelson and Stathers, 2009; Vincent *et al*., 2010). The social constructions of gender roles and responsibilities mean that women are typically disadvantaged relative to men. Due to greater levels of out-migration by men, women are disproportionately represented in rural areas, and globally women in rural areas make up one quarter of global population (Inter-Agency Task Force on Rural Women, 2012). As a result, it is essential that a chapter on rural areas be gender-sensitive. This box summarises the gender elements of vulnerability, impacts, and adaptation in rural areas.

Gendered differences exist in experiences of the multiple stresses that affect rural areas. Access to land shows strong differences between men and women, as do labour markets (FAO, 2010) and access to non-farm entrepreneurship (Rijkers and Costa, 2012). Less than 20% of the world's landholders are women, but women still play a disproportionate role in agriculture. On average women make up around 43% of the agricultural labour force in developing countries; in South Asia almost 70% of employed women work in agriculture, and more than 60% in sub-Saharan Africa (Inter-Agency Task Force on Rural Women, 2012). Climate change increases vulnerability through male out-migration that increases the work to women; cropping and livestock changes that affect gender division of labour; increased difficulty in accessing resources (fuelwood and water) and increased conflicts over natural resources. These factors can make rural women more vulnerable than men, in terms of reductions in resources, potential loss of employment and raised food prices (e.g. Tandon, 2007; Rossi and Lambrou, 2008; Ruel et al, 2009). Evidence for gendered vulnerability to climate change in rural areas exists in Africa (e.g. Omolo, 2011; Huisman, 2005).

In additional to differential access to resources and property rights, gender-ascribed social roles and responsibilities can also mean that women are differentially affected by climate extremes. Women are generally more vulnerable to the impacts of extreme events, such as floods and tropical cyclones. This occurs due to a combination of being close to the homestead, not having access to information (such as early warnings), and lacking the skills to survive, such as swimming. As well as differential immediate effects of extreme events, women are typically disadvantaged relative to men in the relief and recovery period (Alam and Collins, 2010). Lack of gender-sensitivity in emergency camps (e.g. different sanitation facilities) can put women's personal security at risk; and as social constructions of gender determine that they should be responsible for taking care of other household members; although there have been calls to add nuances to these differences (Cupples, 2007). Although there is little agreement in the role of environmental migration in response to climate change, women are disadvantaged in accessing this option (Foresight: Migration and Global Environmental Change, 2011).

Enabling adaptation of men and women requires a gender-sensitive approach that recognises and addresses the differential vulnerabilities. Not taking a gender-sensitive perspective can risk reinforcing existing vulnerabilities (Figueiredo and Perkins, 2012; Arora-Jonsson, 2011). However it is also important to move beyond generic gender differences and examinegender alongside other factors (Tschakert, 2013). Government interventions to improve production through cash-cropping and non-farm enterprises, for example, typically advantage men over women since cash income is seen as a male activity in rural areas (Gladwin et al, 2001); whilst rainwater and conservation-based adaptation initiatives may require additional labour which women do not necessarily have (Baiphethi et al, 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Below et al, 2012; Goulden et al, 2009; Vincent et al, 2010). Similarly recognising preferences in accessing adaptation-enabling information is important: in South Africa, for example, it was observed that women preferred to hear seasonal forecasts through extension agents, as opposed

to over the radio like men (Archer, 2003); whilst in Ghana information is broadcast over the radio, but women only hear it if they happen to be in the company of men who are listening (Nab and Korenteng, 2012).

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9.3.5.2.6. Knowledge and information

Knowledge and information debates are very much linked to institutions, since knowledge is in itself is a component of institutions. Lack of access to information and knowledge of rural people is suggested as a factor that increases vulnerability, mostly among poor people, which can also affect the above mentioned drivers. What is not so much agreed in the literature is what type of knowledge is best to reduce vulnerability. Some authors suggest the need for local responses and indigenous knowledge to reduce vulnerability (Valdivia *et al*., 2010), and call for an integration of local knowledge into climate policies (Nyong *et al*., 2007), while Bellon *et al*., (2011) state that local knowledge and traditional institutions are too local, and in some contexts gathering information from further away is important. They find that to face the forecasted climatic changes, the geographical area of exchange of seeds should be larger than the one covered by the traditional systems of seed exchange.

Access to information is also important, shared knowledge and lessons learned from previous climatic stresses provide vital entry points for social learning and enhanced adaptive capacity (Tschakert, 2007). However, access to information is not always a guarantee of success. Coles and Scott (2009) found that in Arizona, despite ample access to weather forecasting, ranchers did not rely on such information, implying that changes are required to make more attractive information to users, as well as to understand prevailing local cultures and norms.

It is also important in the debate how knowledge is produced, managed, and disseminated within the formal institutional structure to address vulnerability issues. A local case-study in Sweden shows that limited co-operation between local sector organisations, lack of local co-ordination, and an absence of methods and traditions to build institutional knowledge exist, posing barriers to manage vulnerability (Glaas *et al*., 2010). To address this it is suggested that local institutional structure must be flexible and encourage institutional learning and knowledge transfer, implementing communication mechanisms between public authorities, other knowledge producers, and civil society to favour more reliable assessments of local vulnerabilities (Glaas *et al*., 2010). Moumouni and Idrissou (2013 and forthcoming) examine the lack of co-ordination in Benin between climate policies and the policies and practices which govern agricultural research and extension, while good practice at project level could be harnessed to foster collective learning of farmers and other agricultural stakeholders, and thus adapataion to climate change.

The importance of access to knowledge and information has also been addressed with other drivers, suggesting that the combined pressure of climate change–induced decreased access to resources, the institutional vacuum, the loss of esteem for authorities, and the loss of trust in cultural knowledge accentuates the need to address governance to improve access to resources, access to information, mutual understanding of the role of knowledge systems for the interpretation of climate change and variability, and relevant institutional capacities (Kronik and Verner, 2010). In this direction, an alternative mode of interaction to the science and practice one-way interaction often used to address vulnerability, adaptation and resilience, in which different experts, risk-bearers, and local communities are involved and knowledge and practice is contested, co-produced and reflected upon it (Vogel *et al.,* 2007).

9.3.5.3. Outcomes

The outcome of vulnerability is the result of and interaction of the driving forces that determine vulnerability. This section analyses how different drivers may affect specific vulnerable groups in rural areas, that is pastoralists, mountain farmers and artisanal fisherfolk. Box 9-3 takes a specific economic sector important in rural areas, and demonstrates the interplay of vulnerability and exposure.

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Box 9-3. Tourism and Rural Areas

The three major market segments of tourism most likely to be affected by climate change are rural-based, namely, coastal tourism, nature-based tourism and winter sports tourism) (Scott *et al*., 2012). Tourism is a significant rural landuse in many parts of the world, yet compared to other economic sectors in rural areas, the impacts of climate change are typically under-researched. In the Caribbean, for example, tourism has overtaken agriculture in terms of economic importance, with several regional states (including the Bahamas, the Cayman Islands and St Lucia) receiving more than 60 percent of their GDP from this industry (Meyer, 2006). Coastal environments elsewhere in the world are also characterised by dependence on rural tourism, and are known to be vulnerable to cyclones and sea level rise (Klint *et al.,* 2011; Payet, 2007).

Terrestrial natural resource-based tourism is also a significant foreign exchange earner in many countries. In sub-Saharan Africa, between 25 and 40% of mammal species in national parks are likely to become endangered by 2080, assuming no species migration (and 10-20% with the opportunity for migration) (Thuiller *et al.,* 2006). There are also many rural environments viewed as "iconic" or having cultural significance that are vulnerable to climate change. In South Africa, for example, the Cape Floral (fynbos) ecosystem has a high level of species endemism which will be vulnerable to the projected increase in dry conditions (Midgley *et al*., 2002; Boko *et al*., 2007). The projected increase in climate change-related hazards, such as glacial lake outbursts, landslides, debris flows and floods, will likely affect trekking in the Nepali Himalayas (Nyaupune and Chhetri, 2009).

The development of tourism has, in many cases, increased levels of exposure to climate change impacts. In the Caribbean, for example, tourism has led to considerable coastal development in the region (Potter, 2000), which may exacerbate vulnerability to sea-level rise. In many cases, the carbon emissions resulting from participating in rural tourism threaten the very survival of the areas being visited. This is often the case for very remote locations, for example polar bear tourism in Canada (Dawson *et al*., 2010), dive tourism in Vanuatu (Klint *et al*., 2012). Although on aggregate resource consumption of tourists and locals has been shown to be similar in developed county contexts (e.g. in Italy – Patterson *et al*., 2007); in many developing countries resources used by tourists are much higher than locals (e.g. in Nepal - Nepal, 2008).

Despite the potential impacts of climate change on rural tourism, there is little evidence of significant concern, which impedes adaptive responses. Surveys in both the upper Norrland area of northern Sweden and New Zealand showed that climate change is not perceived to pose a major threat in the short term, relative to other business risks perceived by small business owners and tourism operators (Broudera and Landmarka, 2011; Hall, 2006).

That said, there is evidence that, with planned adaptation, tourism can flourish in rural areas under climate change. In the Costa Brava region of Spain, for example, although the increasing temperatures and reduced water availability is projected to negatively impact tourism in the current high seasons, there is scope to shift to the current shoulder seasons, namely April, May, September and October (Ribas *et al*., 2010). Recognition of the opportunities for adaptation have also necessitated reassessment of the extent of the potential impacts of climate change on the tourism industry in rural areas. Using snowmaking as an adaptation in the eastern North American ski industry suggests that even the warmest scenario only poses a minor risk to four out of six areas (Scott *et al*., 2006).

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9.3.5.3.1. Pastoralists

Pastoralists have developed successful strategies for responding to climate variability, especially what Krätli *et al.* (2013) refer to as "strategic mobility" in pursuit of high-quality grazing, in combination with shorter-term coping strategies (Morton, 2006), for example in the Afar region of Ethiopia (Davies and Bennett, 2007). These strategies suggest that a strong adaptive capacity is intrinsic to pastoralism (Davies and Nori, 2008). However, traditional practices such as pastoral mobility are declining , which increases the vulnerability of people in arid and semiarid

regions (Lioubimtseva and Henebry, 2009; Fraser *et al*., 2011). Drought may become famine because of privatization policies that limit pastoral mobility making pastoralists dependent on rainfed agriculture (Smucker and Wisner 2008). Furthermore, the lack of other alternatives in certain marginal areas where animals are the only secure assets can lead to overstocking and overgrazing, and thus, to increased vulnerability of pastoralism (Cooper *et al*., 2008).

These constraints arise from a range of social, economic, environmental and political pressures external to pastoralism that bring about "induced vulnerability" (Krätli *et al.,* 2013): especially encroachment on rangelands, inappropriate land policy, undermining of pastoral culture and values, and economic policies promoting uniformity and competition over diversity and complementarity. Other authors list as constituents of increased vulnerability: population growth; increased conflict over natural resources; changed market conditions and access to services under liberalisation; concentration of political power in national centres; and perceptions that pastoralists are backward (Dougill *et al*., Fraser, and Reed, 2010; Rivera-Ferre and López-i-Gelats, 2012; Smucker and Wisner, 2008; Dong *et al,*. 2011). These in turn can be seen as results of what Reynolds *et al*., (2007) conceptualise as two key features of dryland populations: remoteness, and distance from the centres and priorities of decision-makers or "distant voice". However Dong *et al*. (2011) and Sietz *et al*. (2011) stress the geographic differentiation of pastoral systems (and more broadly of dryland systems with which they overlap).

9.3.5.3.2. Mountain farmers

Mountain ecosystems have been identified as extremely vulnerable to climate change (IPCC 2007), and thus populations have a high exposure to climate change. A detailed understanding of climate change impacts in mountain areas is difficult because of physical inaccessibility and scarcity of resources for research in mountain states and regions (Singh *et al.,* 2011), as well as more generic uncertainties relating to climate projection. However, agreement exists that impacts will include melting of glaciers, flooding or increasing probability of fires (Nogués-Bravo *et al*., 2007; Beniston, 2003). This will in turn have strong impacts on agriculture and livestock-based activities in these areas (e.g., changes in plants, pastures and water availability; slope instability; new diseases) as well as on tourism-based activities (Scott, 2006). But mountain dwellers, as pastoralists in drylands, are adapted to live in steep and harsh and variable conditions, and thus have a variety of strategies to adapt and foster resilience to changing climatic conditions. However, to develop their strategies they need to overcome other drivers that can affect their vulnerability in different contexts. For instance, in most developed countries, mountains are becoming depopulated (Gellrich *et al*., 2007; López-i-Gelats, 2013; Gehrig-Fasel *et al*., 2007) given the extreme climatic conditions, their remoteness and subsequent isolation, while in developing countries there is a trend towards increasing population (e.g. tropical mountain areas) (Lama and Devkota, 2009; Huber *et al*., 2005). The impacts of the projected warming on mountain farming, as well as their adaptation strategies, differ spatially because the socioeconomic role of mountains varies significantly between industrialized and industrializing or non-industrialized countries (Nogués-Bravo *et al*., 2007). Mountain grasslands in developed countries are usually managed via a sub-exploitation model that involves the intensive use of the most productive areas and the abandonment of those regions where production is economically less viable (López-i-Gelats *et al*., 2011). In contrast, mountain grasslands in developing countries remain centers of fodder and livestock production. Thus, two general trends are identified in world mountain grasslands, while temperate grasslands tend to suffer from conversion to agriculture, and land abandonment where livestock raising is less feasible (Gellrich *et al*., 2008); in tropical grasslands the main cause of degradation is overgrazing, linked to processes of demographic growth. Land privatization, loss of grazing rights, or changes in land use (e.g., development of infrastructure) also affect mountain farmers both in developed and developing countries (Tyler *et al*., 2007; Xu *et al*., 2008).

9.3.5.3.3. Artisanal fisherfolk

Small coastal and riparian rural communities face several drivers that increase their vulnerability, which remain largely ignored by mainstream fisheries policy analysts; for example, the likely impact of demographic, health and disease trends, or of wider development policy trends (Hall, 2011), pressure from other resources (e.g. water, agriculture, coastal defense), unbalanced property-rights; lack of adequate health systems, potable water, or sewage

and drainage (Badjeck *et al*., 2010). The most important drivers affecting small-scale fisheries can be grouped into: international trade and globalization of markets; technology; climate and environment; health and disease; demography; development patterns and aquaculture; for instance, freshwater fisheries are threatened by increasing irrigation, while vulnerability of coastal fisheries increases with mangrove loss to aquaculture facilities in response to growing markets for prawns (Hall, 2011). Another difficulty faced by fisheries-based livelihoods is the neglect of governments and researchers, which is more centred on industrial fishing leaving aside artisanal ones (Mills *et al*., 2011). Management systems, property rights and institutions are extremely important in fisheries. Given the complexity of fisheries management and the particular open ecosystem in which this activity is carried out, the existing discussions about fisheries management are complex but also advanced in terms of introducing ecosystem rights and participation principles into management (Andrew and Evans, 2011; Charles, 2011), which in other fields are essential for reducing vulnerability, adapting to climate change and favouring sustainable societies.

9.4. Adaptation and Managing Risks

9.4.1. Framing Adaptation

As the previous sections outlined, it is virtually certain that there will be impacts of climate change in rural areas in both developed and developing countries for which adaptation is required. AR4 stated with very high confidence that adaptation to climate change is already taking place, but on a limited basis. Since then, evidence has increased such that there is very high confidence that adaptation is taking place in rural areas. Many adaptations build on examples of responses to past variability in resource availability, and it has been suggested that the ability to cope with current climate variability is a prerequisite for adapting to future change (Cooper *et al*., 2008). At the same time, however, it cannot be assumed that past response strategies will be sufficient to deal with the range of projected climate change. In some cases, existing coping strategies may increase vulnerability to future climate change, by prioritising short–term resource availability (O'Brien *et al*., 2008; Adepetu and Berthe, 2007). In developing countries, there is high confidence that adaptation could be linked to other development initiatives aiming for poverty reduction or improvement of rural areas (Nielsen *et al*., 2012; Hassan, 2010; Eriksen and O'Brien, 2007). In Ethiopia, for example,"low regrets" measures to respond to current variability are important to shift the trajectory from disaster-focused to longer-term vulnerability reduction (Conway and Schipper, 2011).

9.4.2. Decisionmaking for Adaptation

Decision-making for adaptation takes place at a variety of levels, and can be public or private. At the national and local levels, law and policies can enable planned adaptation (Stuart-Hill and Schulze, 2010). Evidence for policies to support adaptation exists from across the world, but tends to be greater in developed countries. In Australia, the Queensland government has set policies in anticipation of sea level rise, and in New Zealand the revised Coastal Policy Statement requires a minimum 100-year time frame for coastal planning (see Box 25-2). Australia also has a comprehensive water resources policy designed to deal with scarcity (see Box 25-3). In northern Canada, some territorial governments in Northern Canada have developed climate change strategies that promote further adaptation such as providing hunter support programs (Ford et. al., 2010)(see also chapter 26). However, in the Great Plains of the US, less than 20% of jurisdictions have developed plans on either climate adaptation or climate mitigation (Romsdahl *et al*., 2013).

At the local level, many adaptations are examples of private decisions for adaptation. As shown with very high confidence in AR4, such adaptation decisions are embedded in the inter-relationship of a variety of social factors in which climate drivers are only one consideration (Crane *et al*., 2011). An example of where public policy can support private adaptation is in index-based insurance schemes. In Africa where understanding of insurance is low, participation rates can be improved by using simulation games, as trialed in Ethiopia and Malawi, or by more conventional training methods (Patt *et al*., 2010). Data from India, Africa and South America shows that the trust that people have in the insurance product and the organisations involved in selling and managing it may be more important than economic factors, such as the size and timing of the premium and potential payouts (Patt *et al*., 2009). However, private decisions often take place in the context of national policies and laws, which are not always

mutually-supportive (Stringer *et al.*, 2009), especially in the agropastoral sector where settlement is encouraged (Awuor *et al.*, 2011).

One major difference between public and private decision-making is that that latter is typically more responsive. An analysis of agricultural water schemes in South America, for example, found that private irrigation schemes increase in response to a warmer climate, whereas public ones do not, and that they are taken gradually (Seo, 2011b). Participatory stakeholder processes to inform public policy and law can take time. A case study of a resettlement programme in Mozambique showed that farmers and policymakers disagreed about the seriousness of the climate risks, and the potential negative consequences of proposed adaptive measures (Patt and Schroeter, 2008). In Bangladesh, the ambitious national Flood Action Plan (FAP) did not receive support from NGOs, who embarked upon an anti-FAP movement and attained what they perceived to be a more people-oriented national water policy (Mallick *et al.*, 2005).

There is increasing evidence that public decision-making for adaptation can be strengthened by understanding the decision-making of rural people in context (Bryan *et al.*, 2009). Local and indigenous knowledge for responding to weather events and a changing climate has been observed in, for example, the Peruvian Andes (see chapter 26), Samoa (Lefale, 2010 – see chapter 29), the Solomon Islands (Rasmussen et al, 2009 – see chapter 29), Canada (Ford et al, 2007) and the Indo-Gangetic Plains (Rivera-Ferre et al, 2013).

9.4.3. Practical Experiences of Adaptation in Rural Areas

There are wide-ranging and manifold examples of adaptation in rural areas, in both developed and developing countries. These practical experiences of adaptation are found in agriculture, water, forestry and biodiversity, and fisheries.

9.4.3.1. Agriculture

Agricultural societies have a history of responding to the impacts of change in exogenous factors, including (but not limited to) weather and climate (Mertz *et al.*, 2009). They undertake a range of adjustment measures relating to their farming practices – for example, planting, harvesting and watering/fertilizing existing crops; using different varieties, diversifying crops; implementing management practices such as shading and conservation agriculture (see Table 9-6).

[INSERT TABLE 9-6 HERE
Table 9-6: Examples of adaptations in the agricultural sector in different regions.]

Conservation agriculture shows promising results and can be used as an adaptation (Nyala *et al.*, 2011) and for sustainable intensification of production (Pretty *et al.*, 2011), with significant yield productions observed in South Asia and southern Africa (Erenstein *et al.*, 2012). In other cases, the potential effectiveness of adaptation under future climate scenarios has been modeled, for example in Cameroon (Tingem and Rivington, 2009), and for the African continent (Seo, 2011a). Water management for agriculture is also critical in rural areas under climate change, for example the use of rainwater harvesting (Biacin *et al.*, 2011; Kahinda *et al.*, 2010, Vohland and Barry, 2009; Rivera-Ferre *et al.*, 2013), and more efficient irrigation, particularly in rural drylands (Thomas, 2008).

Adaptations are also evident among small-scale livestock farmers (Rivera-Ferre and López-i-Gelats, 2012; (Kabubo-Mariara, 2009, 2008), who use many different strategies, including changing herd size and composition, grazing and feeding patterns, or diversifying their livelihoods, also they may use new varieties of fodder crops suited to the changing conditions (Salema *et al.*, 2010).

Diversified farms are more resilient than specialized ones (Seo, 2010); but rural societies also diversify their income sources beyond agriculture, which in many contexts allows them to reduce their risk exposure. Examples include the exploitation of gums and resins in Kenya (Gachathi and Eriksen, 2011).There may be some rural areas, however,

where limits to agricultural adaptation are reached, and thus the only option that remains is to migrate or diversify away from farming (Mertz *et al.*, 2011).

9.4.3.2. Water

As well as being an important input to agriculture, adaptation in water resources in general is critical in rural areas. Given projected reductions in water availability, improved management is required. The extent to which such adaptation measures have been implemented to date varies: in a study from Europe, Africa and Asia, the Elbe and Rhine basins had the highest level of water resource management measures in place, followed by the Orange and Guadiana, with lower levels in the Amu Darya and Nile Equatorial Lakes (Krysanova *et al.*, 2010). In the Middle East and North Africa, whilst supply-side measures are advanced, little attention has been paid to the demand-side measures that will be critical in a changing climate (Sowers *et al.*, 2010). In the cases of transboundary basins additional barriers exist to adaptive management measures, particularly in Africa (Goulden *et al.*, 2009a), although examination of potential institutional designs has been undertaken (Huntjens *et al.*, 2012). The need for effective water management for adaptation therefore exists not only at the basin level, but at a higher resolution, for example in human settlements and towns (Mukheibir, 2008).

Whilst the majority of focus on adaptation concerning water relates to its availability, it is also important to remember that many rural areas are subject to riverine or coastal flooding. In the low-lying Netherlands protection measures have been employed, including increasing river runoff, increasing storage for water (Delta Committee, 2008; Kabat *et al.*, 2009), and small scale containment of flood risks through increasing compartmentalisation (Klijn *et al.*, 2009). In the Mekong Delta in Vietnam, Columbia University's Center for International Earth Science Information Network has projected that a "one-meter sea-level rise could result in the displacement of more than seven million residents in the delta, and a two-meter rise would double to 14 million- or 50 percent of the delta residents." An increase in flood frequency and magnitude has threatened residents' lives and created instability in crop fields. As rapid industrialization has placed stresses on the environment and Vietnam's natural resources, many people in Mekong have adapted by moving east to cities with rapid economic growth. The government's "living with floods" program has encouraged rice farmers to shift to aquaculture, while the planned relocation of 20,000 "landless and poor households" has altered social networks and livelihoods (De Sherbinin *et al.*, 2011).

[INSERT TABLE 9-7 HERE
Table 9-7: Examples of adaptations in the water sector observed in different regions.]

9.4.3.3. Forestry and Biodiversity

Effective management is also essential for adaptation of forests and biodiversity to climate change. As with water resources, forests can adapt through management of forest fires, silvicultural practices, and the conservation of forest genetic resources. Ecological restoration, where required, is another effective adaptation measure – Benayas *et al.* (2009), in a meta-analysis of 89 studies, estimated this technique enhances the provision of biodiversity and environmental services by 44% and 25%, respectively. Moreover, ecological restoration increases the potential for carbon sequestration and promotes community organization, economic activities and livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon *et al.*, 2011; Rodrigues *et al.*, 2011). In other parts of Africa, the systematic analysis of current policies and practices in order to understand the nature and extent of intervention required is often lacking (Fobissie *et al.*, 2009).

Forest resources have been shown to play a role in enabling adaptation during extreme events in Zambia, Mali and Tanzania, although should take place within a managed context to ensure sustainability (Robledo *et al.*, 2011). As the climate changes, part of adaptive management may entail modification of existing biodiversity management practices. In addition to land and water management and law and policy, direct species management is important (Mawdsley *et al.*, 2009). In terms of managing protected areas, to maintain appropriate habitats a network approach may be effective (Hole *et al.*, 2011).

Community involvement in natural resources management and biodiversity conservation is highlighted as critical, with community-managed natural areas experiencing lower rates of deforestation than non-community-managed ones (Porter-Bolland et al, 2012). In Central and South America, protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and that in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas (Nelson and Chomitz, 2011). Reflecting the growing evidence for community-based management and wise use, an emerging mechanism for ecosystem-based adaptation includes payment for ecosystem services (PES) (Montagnini and Finney, 2011), although there is virtually no peer-reviewed literature on PES specifically for emissions reduction (Campbell, 2009). Particularly developed in Central and South America (see table 27-5 for examples of PES schemes in Latin America), communities can be paid for collecting scientific data to contribute to research and monitoring protocols (Luzar *et al*., 2011), or for actively managing natural resources.

9.4.3.4. Fisheries

Adaptation in marine ecosystems is also of relevance to rural areas. Bleaching of coral reefs through rising temperatures causes habitat loss which, in turn, affects fisheries. Selective use of fishing gear is a recommended management measure, based on 15 global sites, to ensure sustainable harvesting of remaining fish stocks (Cinner *et al*., 2009). As with other ecosystems, the extent to which adaptation is required will depend on existing capacity. Of 5 countries in the southwestern Indian Ocean, the environmental sensitivity in Mauritius is offset by the higher adaptive capacity (based on a multi-faceted social adaptive capacity index they used in the study), although the more environmentally-sensitive parts of Madagascar will be priorities for intervention assistance (McClanahan *et al*., 2009). As with terrestrial natural resources, evidence from the marine resources sphere shows that fisheries co-management, involving local fishermen and allowing limited extraction of resources, favour a balance between resource conservation and livelihoods, e.g in Brazil (Francini-Filho and Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations (Hastings, 2011; Moura *et al*., 2009). Given the complexity of fisheries management and the particular open ecosystem in which this activity is carried out, the existing discussions about fisheries (adaptive) management are complex but also advanced in terms of introducing ecosystem, rights and participation principles into management (Andrew and Evans 2011; Charles 2011), which are essential to reduce vulnerability and adapt to climate change. Box 25-6 details vulnerability and adaptation in rural areas in Australia.

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Box 9-4. Drought Adaptation in Rajasthan

Rajasthan in India is located in an arid ecological zone and experiences severe droughts, a condition that communities have learned to cope with through conservative use of natural resources. Ways in which communities have adapted to drought include ending production of crops such as wheat and cotton that require a large amount of water, storing fodder for times of drought and scarcity, using savings or borrowing “from cooperatives and banks” for drinking water well construction, bunding fields, digging and deepening ponds and wells to retain water, growing medicinal plants to contribute to revenue, making compost using earthworms for environmentally friendly fertilizer. With the help of a local NGO, women have also formed a self-help group (SHG) to collect money to lend to the needy during emergencies. Additionally, a government Food-for-Work Programme helps provide communities with wheat, cash, and subsidized fodder (Chatterjee *et al*., 2005).

_____ END BOX 9-4 HERE _____

_____ START BOX 9-5 HERE _____

Box 9-5. Adaptation to Extreme Events in Jamaica

Extreme weather events and severe droughts have badly affected Jamaica’s households, communities, and agriculture since the mid 1990’s. These changes will likely contribute to poverty and stunt Jamaica’s growth and

productivity. The adaptation methods that have already been used by farmers in St. Elizabeth, which is considered the breadbasket of Jamaica, include planting methods such as "quick crops and the scaling down of production during the dry season," when they will mature and be ready for the market during the tourist season. This also enables farmers to generate enough income to invest more during the rainy season to grow primary crops. Thus, farmers try to minimize risk because they are especially vulnerable to the dry season- their success during the rainy season is dependent on production during the dry season. Another adaptive strategy is to plant crops with multiple uses and crops that will be more tolerant to dry spells. In southern St. Elizabeth, a dry area, successful crop production depends on moisture retention, which is increase with practices such as "mulching, edging or perimeter planting, drip irrigation and managing the application of water to plants". During droughts, some farmers will "sacrifice a portion of the crops under cultivation," apply thicker mulching, borrow or share money for water, and using fertilizer on leaves. To recover from drought, farmers "scale down" so that their crops are more manageable and can grow successfully (Campbell *et al.*, 2011).

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Box 9-6. Adaptation Initiatives in the Beverage Crop Sector

One of the leading initiatives to prepare small holder producers of beverage crops for adaptation to climate change is the AdapCC project which worked with coffee and tea producers in Latin America and East Africa (Schepp, 2010). This process used risk and opportunity analysis and participatory capacity building (CafeDirect/GTZ, 2010) to help farmers identify changes in management practices to both mitigate their contribution to climate change and adapt to the changes in climate they perceived to be occurring. In general the actions for adaptation were a reinforcement of principles of sustainable production, such as using tree shade.

The Coffee Under Pressure project of CIAT and Green Mountain Coffee has complemented the models of changes in coffee distribution with models of changes in distribution of 20 other potential crops that may have potential to replace coffee where it will cease to be viable in the future. This has been complemented with detailed studies of the vulnerability of producers in terms of exposition, sensitivity and capacity to adapt to climate change (Baca *et al.*, 2010). This indicates that there is a considerable variability in the overall vulnerability to climate change between different communities in the same region and even families within the same community. Facilitating processes of adaptation in this context will be a challenge, but supports the need for participatory community adaptation processes that would enable families to implement strategies appropriate to their own circumstances and capacity.

Policy recommendations to support adaptation in these sectors (Eakin *et al.*, 2011; Laderach *et al.*, 2011; Schepp, 2010; Schroth *et al.*, 2010) have prioritized the follows interventions to support adaptation:

- Community-based analysis of climate risks and opportunities as a basis for community adaptation strategies
- Improved recording and access to climate information including medium and long-term predictions
- Sustainable production techniques including soil and water conservation, shaded production systems, diversification of production systems
- Development of new varieties with broader adaptability to climate variation, higher temperatures and increased drought tolerance
- Financial support to invest in adaptation and reduce risks through climate insurance
- Organization of small producers to improve access to knowledge, financial support and coordinate implementation
- Environmental service payments and access to carbon markets to support sustainable practices
- Development of value chain strategies across all actors to support adaptation and increase resilience across the sectors.

There are possibilities for synergy between adaptation and mitigation. The sustainability standards Rainforest Alliance and Common Code for the Coffee Community are piloting climate-friendly standards for producers that aim to reduce the GHG emissions from agricultural practices, increase sequestration of carbon in soils and trees, but also prepare producers for adapting to climate change (SAN, 2011; Linne, 2010). The later consists of improved

understanding of climate impacts and promoting sustainable production practices to increase resilience in the production systems.

_____ END BOX 9-6 HERE _____

9.4.4. Limits and Constraints to Rural Adaptation

The Fourth Assessment Report stated with very high confidence that there are substantial limits and barriers to adaptation (Adger *et al*., 2007). Since that time additional evidence has shown that barriers do exist to adaptation – and that these barriers are both hard (physical) and soft (financial, social and cultural).

Lack of access to credit, water and land are major factors inhibiting adaptation for farmers in Africa and Asia. A multinomial logit analysis of climate adaptation responses suggested that access to water, credit, extension services and off-farm income and employment opportunities, tenure security, farmers' asset base and farming experience are key to enhancing farmers' adaptive capacity (Gbetibouo *et al*., 2010). A multinomial choice model fitted to data from a cross-sectional survey of over 8000 farms from 11 African countries showed that better access to markets, extension and credit services, technology and farm assets (labour, land and capital) are critical for helping African farmers adapt to climate change. Hence education, markets, credit and information about adaptation to climate change, including technological and institutional methods are important (Hassan and Nhemachena, 2008).

Rural households' lack of access to technologies and markets is also a major barrier to adaptation for certain production systems. According to a study of adoption of improved, high yield maize in Zambia, production and price risks could render input use unprofitable and prevent rural households from benefiting from technological change crucial for adaptation (Langyintuo and Mungoma, 2008). The severe 1997 drought in the Central Plateau of Burkina Faso highlighted that household with a larger resources base took the advantage of distress sales and high prices of agricultural commodities (Roncoli *et al*., 2001). A nationally representative rural household survey in Mozambique from 2005 shows that, overall, using an improved technology (improved maize seeds, improved granaries, tractor mechanization, and animal traction) did not have a statistically significant impact on household income. However when distinguishing between households using improved technologies, especially improved maize seeds and tractors, and those who do not, households who had better market access had significantly higher income (Cunguara and Darnhofer, forthcoming). Social characteristics of households heads and culture both affect access to adaptation options, based on modeled data from the Nile basin of Ethiopia (Deressa *et al*., 2009) and evidence from Burkina Faso (Nielsen and Reenberg, 2010), respectively.

Although access to credit, water, technologies and markets are barriers, more fundamental is access to information. Since adaptation strategies involve dealing with uncertainty, whether stakeholders have access to information for decision making and how they perceive and utilize this information affects their adaptation choices (Sheate *et al*., 2008; Patt and Schröter, 2008; Dockerty *et al*., 2006). Relevant information includes that on agricultural technologies that can be used in adaptation, but in developing countries agricultural research and extension systems are not integrated with climate planning to deliver this, as discussed by Moumouni and Idrissou (2013) for Benin. There is now an important literature on dissemination of short-term or seasonal weather forecasts to farmers in developing countries, as detailed in Box 9-7.

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Box 9-7. Factors Influencing Uptake and Utility of Climate Forecasts

So far the uptake of information has been suboptimal (Vogel and O'Brien, 2006), but the potential for improved prediction and effective timely dissemination has been noted in South Africa (Archer et al, 2007; Klopper et al, 2006) and also in Ethiopia (Bryan et al, 2009). There have been attempts to assess factors influencing uptake and utility of climate forecasts. Agent-based social simulation models show that to be effective in reducing climate risk, trust in forecasts has to be high, and they have be right 60-70% of the time to benefit smallholder farmers (Ziervogel *et al*., 2005). As well as trust, the effects of user wealth, risk aversion, and presentational parameters, such as the

position of forecast parameter categories, and the size of probability categories, on perceived value of seasonal forecasts have been investigated (Millner and Washington, 2011). An assessment of the extent to which climate change scenarios are currently used in developing adaptation strategies within the agricultural development sector in Africa shows that annual climate information (such as seasonal climate forecasts) is used to a certain extent to inform and support some decisions, yet climate change scenarios are rarely used at present in agricultural development (Ziervogel and Zermoglio, 2009). Although, there is a large and growing literature on the role of seasonal forecasts, in particular on the needs of rural end-user groups, e.g. smallholder farmers in a mountainous village in southern Lesotho (Ziervogel, 2004), the optimal use of seasonal forecasts in risk management by smallholder farmers is largely limited by constraints related to legitimacy, salience, access, understanding, capacity to respond and data scarcity (Hansen *et al*., 2011).

The socio-cultural context of participatory processes in the dissemination and use of seasonal forecasts is important and affects who participates and what they gain (Peterson *et al*., 2010). Rural producers in three ecological zones of Burkina Faso who had taken part in appropriate participatory processes were statistically more likely to understand the probabilistic aspect of the forecasts and their limitations, to use the information in making management decisions and through a wider range of responses than those who had not taken part (Roncoli *et al*., 2009). Evidence from Malawi shows that forests can be important in reactive coping by providing food during shortages and a source of cash for coping with weather-related crop failure – but households most reliant on forests have low income per person, are located close to the forest, and are headed by individuals who are older, more risk averse, and less educated than their cohorts (Fisher *et al*., 2010). Gender differences have been observed in preferred dissemination channels (Box 9-2). Debates over forecast skill and farmer skill are also common to other parts of the world such as the USA, where interviews with farmers in Georgia showed that the social nature of information processing and risk management bears upon the ways farmers may integrate climate predictions into their agricultural management practices (Crane *et al*., 2010).

Stakeholder networks have been used to map forecast dissemination in Lesotho, and are useful for identifying obstacles (Ziervogel and Downing, 2004). There are promising signs for the integration of scientific-based seasonal forecasts with indigenous knowledge systems (Ziervogel *et al*., 2010). Ensuring improved validity and utility of seasonal forecasts will require collaboration of researchers, data providers, policy developers and extension workers (Coe and Stern, 2011), as well as with end users. Additional opportunities to benefit rural communities come from expanding the use of seasonal forecast information for coordinating input and credit supply, food crisis management, trade and agricultural insurance (Hansen *et al*., 2011). Attempts to use longer term crop forecasting options based on large-area seasonal crop yield forecasting and, genotypic adaptation based on long-term climate change projections have also been examined (Challinor, 2009). Climate forecasting has also been applied to ecosystem models for use in livestock farming (Boone *et al*., 2004). The IPCC SREX report identified the use of forecasts as a risk management measure (IPCC, 2012)

_____ END BOX 9-7 HERE _____

9.5. Key Conclusions and Research Gaps

9.5.1. Key Conclusions

There is a lack of clear definition of what constitutes rural areas, and definitions that do exist depend on definitions of the urban. Across the world, the importance of peri-urban areas and new forms of rural-urban interactions are increasing. Notwithstanding this, rural areas still account for almost half the world's population, about 75% of the developing world's poor people and 80% of the world's hungry. Rural areas therefore are important for assessing the impacts of climate change and the prospects of adaptation in these areas, constituting a dynamic, spatial category. A lack of focus on the rural sector in policy making increases its vulnerability to climate change. Over 90% of rural people worldwide live in developing countries.

Climate change in rural areas in developing countries will take place in the context of many important economic, social and land-use trends. In different regions, rural populations have peaked or will peak in the next few decades.

The proportion of the rural population depending on agriculture is extremely varied across regions, but declining everywhere. Poverty rates in rural areas are falling more sharply than overall poverty rates, and proportions of the total poor accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising. Hunger and malnutrition are prevalent among rural children in South Asia and Sub-Saharan Africa, and recent hikes and volatility in priced of food exacerbated hunger and malnutrition among rural households, many of which are net food buyers. In developing countries,the levels and distribution of rural policies are affected in complex and interacting ways by processes of commercialisation and diversification, food policies, and policies on land tenure. Rural people are subject to multiple non-climate stressors, including under-investment in agriculture (though there are signs this is improving), problems with land policy, and processes of environmental degradation. Stronger rural-urban linkages through migration, transfer of public and private remittances, regional and international trade, inflow of investment and diffusion of knowledge (through new information and communication technologies) are more positive developments. In industrialized countries, there are important shifts towards multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors and a change from subsidy-based to investment-based policy.

Cases in the literature of observed impacts on rural areas often suffer from methodological problems of attribution, with regard to the difficulties of attributing extreme events to climate change, the status of local knowledge, and the action of non-climate shocks and trends. However, evidence for observed impacts, both of extreme events and other categories, is increasing. Impacts attributable to climate change include declining yields of major crops, some extreme events such as droughts and storms, and geographically-specific impacts such as glacier melt in the Andes.

Future impacts of climate change on the rural economic base and livelihoods, land-use and regional interconnections are at the latter stages of complex causal chains that flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture, livestock, fisheries and less-managed ecosystems. This increases the uncertainty associated with any particular projected impact.

Major impacts of climate change in rural areas will be felt through impacts on water supply, food security and agricultural incomes. In certain countries shifts in agricultural production, of food and non-food crops, could take place. Price rises, which may be induced by climate shocks apart from other factors have a disproportionate impact on the welfare of the poor in rural areas, such as female headed households and those with limited access to modern agricultural inputs, infrastructure and education.

Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security while affecting rural households, depending on whether they are net-buyers or net-sellers of food. The emerging literature suggests that deepening agricultural markets through trade reform and institutional efforts to improve the predictability and the reliability of the world trading system as well as by investing in additional supply capacity of small-scale farms in developing countries could help reduce market volatility and mitigate food supply shortages which might be caused by climate change

Migration patterns will be driven by multiple factors of which climate change is only one. Given these multiple drivers of migration and the complex interactions which mediate migratory decision-making by individual or households, the detection of the effects of climate change on intra-rural and rural-to-urban migration remains a major challenge.

Climate policies, such as encouraging cultivation of biofuels, and payments under REDD, will have significant secondary impacts on land-use, and resulting negative impact on livelihoods, in some rural areas. These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance.

Valuation of climate impacts needs to draw upon both monetary and non-monetary indicators. Most studies on valuation highlight that climate change impacts will be significant especially for the developing regions, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations. The valuation of non-marketed ecosystem services and the limitations of economic valuation models which aggregate across multiple contexts pose challenges for valuing impacts in rural areas.

There are low levels of agreement on some of the key factors associated with vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, and integration into world markets. There is greater agreement on the importance for resilience of access to land and natural resources, flexible local institutions, and knowledge and information, and the association of gender inequalities with vulnerability. Specific livelihood niches such as pastoralism and artisanal fisheries are vulnerable and at high risk of adverse impacts, partly due to neglect, misunderstanding or inappropriate policy towards them on the part of governments.

There is a growing body of literature on successful adaptation in rural areas and constraints upon it, including both documentation of practical experience, and discussion of preconditions. In developing countries adaptation can be linked to other development initiatives aiming for poverty reduction or improvement of rural areas, and "low regrets" measures to respond to current variability can shift the trajectory from disaster-focused to longer-term vulnerability reduction. Prevailing development constraints, such as low levels of educational attainment, environmental degradation, and gender inequalities create additional vulnerabilities which undermine rural societies' ability to cope with climate risks. The supply of information for decision-making, and the role of social capital in building resilience, are key issues.

9.5.2. Research Gaps

Research on climate change in rural areas, which truly takes in their nature as areas with shifting combinations of human activity, in which agriculture (food crops, non-food crops and livestock) is important but not necessarily predominant, and with changing patterns of interaction with towns, is only just beginning. Such research will need to be developed, and extended to rural areas and diverse categories of rural people throughout the world. One relevant area will be that of improving understanding of the respective roles of climate and other factors in rural-urban and rural-rural migration.

Research is required on the valuation and costing of climate change impacts which take note of the complexity and specificity of rural areas, with special emphasis on non-marketed ecosystem services and specific populations that have not as yet been studied. Research is also needed on the trade-offs and synergies between adaptation and mitigation in rural areas, and the appropriate governance structures to enhance synergy.

More research is needed on vulnerability, to identify the most vulnerable areas, populations and social categories, but it should include research on methodological questions such as conceptualizations of vulnerability, assessment tools, spatial scales for analysis, and the relations between short-term support for adaptation, policy contexts and development trajectories, and long-term resilience or vulnerability.

Research is needed on practical adaptation options, not only for agriculture but for non-agricultural livelihoods. Adaptation research must also look at adaptations to institutions, to better enable them to address lack of access to credit, markets, information, risk-sharing tools and property rights. Research into vulnerability, resilience and adaptation must all improve ways to manage knowledge, both local and scientific, for adaptation.

Frequently Asked Questions

FAQ 9.1: Why are rural areas important in the study of climate change impacts, assessments, and vulnerability?
No clear and unique definition of rural areas exist in literature, however it is clear that human settlements do not only include urban areas. Nearly half of the world's population, approximately 3.3 billion, lives in open country areas. This is particularly true in developing and least developed countries, where more than 50% and 75% of the population respectively lives in rural areas. These human settlements are strongly dependent on natural resources and agriculture which influences their socioeconomic structures, and therefore highly sensitive to climate variations – and even recent diversification is typically still natural resource-dependent (e.g. tourism, recreation). In addition, these regions are usually characterized by pre-existing vulnerabilities which can aggravate climate change impacts.

Isolation and marginality remain as factors that significantly affect adaptive capacity in rural areas and increase vulnerability.

There are important differences between rural areas in developing and developed countries. Rural areas in developing countries are characterized by higher prevalence of poverty, isolation and lower human development. In developed countries these features are also present, but they are usually associated and influenced by the proximity to towns, and their role as a place for recreational activities.

FAQ 9.2: What will be the major climate change impacts and adaptations in rural areas across the world?

Given the strong dependence on natural resources, impacts of climate change in rural areas will, be primarily observed as changes in the productivity of primary sectors, such as agriculture, forestry and fishing. Secondary (manufacturing) industries, and the livelihoods and incomes that are based on them, will in turn be substantially affected. Extreme events associated with climate change will also affect rural areas, mainly via heat stress, drought and flooding that impact on infrastructure (i.e. dams, roads, buildings, telecommunications and irrigation systems). Depending on the magnitude these extreme events can trigger economic and political turmoil, as well as migration. Existing isolation and marginalisation create current vulnerability which, in combination with exposure to climate change, increases the risks of adverse impacts.

Adaptation options are context-specific and will depend on the correct identification of relevant risks and the adaptive capacities of rural people with differing access to natural, financial, human and social capital. Examples of rural adaptations include modifying farming and fishing practices, introducing new species and varieties as well as recovering old ones, diversification, water management, modifying infrastructure and technology decisions, and both formal and informal risk sharing mechanisms. Adaptation will also include changes in institutional and governance structures.

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Table 9-1: Major findings of the IPCC Fourth Assessment Report and the International Assessment of Agricultural Science and Technology for Development.

Importance of non-climate trends	Source
The significance of climate change needs to be considered in the multi-causal context of its interactions with other non-climate sources of change and stress (e.g. water scarcity, governance structures, institutional and jurisdictional fragmentation, limited revenue streams for public sector roles, or inflexible land use patterns)	W
Different development paths may increase or decrease vulnerabilities to climate-change impacts	W
Neglect by policy-makers and under-investment in infrastructure and services has negatively affected rural areas	I
Policy neglect specifically disfavours rural women	I
Assessment of climate change impacts on agriculture has to be undertaken against a background of demographic and economic trends in rural areas	E
Global numbers of people at risk from hunger will be affected by climate change, but more by socioeconomic trends as captured in the difference between the SRES scenarios	E
Specific characteristics of smallholder agriculture	
Subsistence and smallholder livelihood systems suffer from a number of non-climate stressors, but are also characterized for having certain resilience factors (efficiencies associated with the use of family labour, livelihood diversity to spread risks)	E
Traditional knowledge on agriculture and natural resources is an important resilience factor	I, E
The combination of stressors and resilience factors gives rise to complex and locally specific impacts, resistant to modelling	E, W
Impacts on agriculture and agricultural trade	
In low-latitude regions, temperature increases of 1-2°C are likely to have negative impacts on yields of major cereals. Further arming has increasingly negative impacts in all regions	E
Increases in global mean temperatures (GMTs) of 2-3 might lead to a small rise or decline (10-15%) in food (cereals) prices, while GMT increases in the range of 5.5°C or more might result in an increase in food prices of, on average, 30%	E
Forestry	
Loss of forest resources through climate change may affect 1.1 billion poor and forest-dependent people, including through impacts on Non-Timber Forest Products.	E
Valuation	
Robust valuations of climate change impact on human settlements are rare	W
Social and environmental costs are poorly captured by monetary metrics: non-monetary valuation methods should be explored	W, I
Adaptation	
Prospects for adaptation depend on the magnitude and rate of climate change	I
Adaptation actions can be effective in achieving their specific goals, but they may have other (positive or negative) effects, including resource competition	I
Diversification of agricultural and non-agricultural livelihood strategies is an important adaptation trend, but requires institutional support and access to resources	E
Links between adaptation and mitigation	
Mitigation and adaptation policies are in many cases, and certainly for agriculture, closely linked	K, E, W

Sources: W = Wilbanks *et al*. 2007; E = Easterling *et al*. 2007; I = McIntyre *et al*. 2009; K = Klein *et al*. 2007

Table 9-2: Major demographic, poverty-related, economic, governance, and environmental trends in rural areas of developed and developing countries.

	Developed countries	**Developing countries**
Demographic Trends	Rural population accounts for 22.3% of the total population (or about 276 million people) (UN-DESA Population Division, 2012). Rural areas account for 75% of land area in OECD countries (OECD 2006). Rural population has peaked (absolute numbers) in Europe and North America. Rural depopulation in some places, but also counter-urbanization with people moving from urban to rural areas elsewhere.	Rural population accounts for 50.3% of the total population (or about 2.5 billion people) in less developed countries (excluding LDCs), 71.5% (or about 608 million people) in the LDCs (UN-DESA Population Division, 2012) Rural population has already peaked in Latin America and Caribbean, East and South East Asia; expected to peak around 2025 in Middle East, North Africa, South and Central Asia; around 2045 in sub-Saharan Africa.
Dependence on agriculture	Agriculture accounts for only 13% of rural employment in the EU (2006), and less than 10% on average across developed countries; however, has a strong indirect influence on rural economies. Increased competition as a result of economic globalization has resulted in agriculture no longer being the main pillar of the rural economy in Europe. Economic policies are primary drivers. (Marsden, 1999, Lopez-i-Gelats, 2009)	Proportion of rural population engaged in agriculture declining in all regions(Figure 9-2).. Agriculture still provides jobs for 1.3 billion smallholders and landless workers (World Bank, 2008). Non-agricultural including labour-based and migration-based livelihoods increasingly existing alongside (and complementing) farm-based livelihoods. Agricultural initiatives and growth still important for adaptation and for small holders in Africa and Asia; (Osbahr *et al.,* 2008; Collier *et al.*, 2008; Kotir, 2010)
Poverty and Inequality	Per capita GDP in rural areas of OECD countries is only 83% of national average (but significant variation within and between countries): driven by out-migration, aging, lower educational attainment, lower productivity of labour, low levels of public services.	Rates of poverty (percentage of population living on less than US $ 2/day) and extreme poverty (percentage of population living on less than US $ 1.25/day) falling in rural areas in most parts of the world; but rural poverty and rural extreme poverty rising in sub-Saharan Africa. Recent price hikes and volatility exacerbated hunger and malnutrition among rural households many of which are net-food buyers (FAOSTATS, 2013). Hunger and malnutrition prevalent among rural children in South Asia and Sub-Saharan Africa (UN, 2010; IFAD, 2010; World Bank, 2007). Figure 9-2 and Table 9-3

Table 9-2 (continued)

Economic, Policy, Governance Trends	Shift from agricultural (production) to leisure (consumption) activities; focus on broader amenity values of rural landscapes for recreation, tourism, and forests, ecosystem services. (Bunce, 2008; OECD, 2006; Rounsevell *et. al.,* 2007) Agricultural subsidies under pressure from international trade negotiations and domestic budgetary constraints. As a result of recent price hikes, domestic price support has been lowered in OECD countries. New policy approach in OECD countries that focuses on investments and targets a range of rural economic sectors and environmental services.	Interconnectedness and economic openness in rural areas have encouraged shifts to commercial agriculture, livelihoods diversification and aid knowledge transfers (section 9.3.3). Interlinkages between land tenure, food security and biofuel policies impact rural poverty (see Chapter 7, section 7.1 and 7.3.2 for further details) Decentralization of governance and emergence of rural civil society. Movements towards land reform in some parts of Asia (Kumar, 2010). Emergence of economies in transition, characterised in places by co-existence of leading and lagging regions; political and democratic decentralization expanding leading to increasing complexity of policy (World Bank, 2007).
Environmental Degradation	Different socio-economic scenarios have varying impacts on land use and agricultural biodiversity (Reidsma *et al.,* 2006).	Resource degradation, environmentally fragile lands subject to overuse and population pressures, exacerbate social and environmental challenges. Multiple stressors increase risk, reduce resilience and exacerbate vulnerability among rural communities from extreme events and climate change impacts (Chapter 13, Section 13.2.6) .
Rural-Urban Linkages and Transformations	Changes in land-use and land-cover patterns at urban-rural fringe affected by new residential development, local government planning decisions, and environmental regulations (Brown *et al*., 2008).	Stronger rural-urban linkages through migration, commuting, transfer of public and private remittances, regional and international trade, inflow of investment and diffusion of knowledge (through new information and communication technologies) (IFAD, 2010). Continued out-migration to urban areas by the semi-skilled and low-skilled, reducing the size of rural workforce (IFAD, 2010). Trend for migration to small and medium-sized towns (Sall *et al*., 2010). Increased volumes of agricultural trade, growing by 5% on average (annually) between 2000-2008 (WTO, 2009). New initiatives of foreign direct investment (FDI) in agriculture in the form of large-scale land acquisitions in developing countries (Anseeuw *et al*., 2012; World Bank, 2010).

Table 9-3: Poverty indicators for rural areas of developing countries.

	Incidence of poverty (%)		Incidence of rural poverty (%)		Incidence of extreme poverty (%)		Incidence of extreme rural poverty (%)		Rural people as % of those in extreme poverty	
	1988	2008	1988	2008	1988	2008	1988	2008	1988	2008
Developing World	69.1	51.2	83.2	80.9	45.1	27.0	54.0	34.2	80.5	71.6

Source: adapted from IFAD, 2010

Table 9-4: Projected changes in areas suitable for production of tropical beverage crops by 2050.

Crop	Countries	Change in climate to 2050	Change in total area by 2050	Change in distribution by 2050
Coffee	Guatemala, Costa Rica, Nicaragua, El Salvador, Honduras, Mexico	2.0-2.5ºC increase in temperature 5-10% decline in total rainfall	Between 38 and 89% decline in area suitable for production	Minimum altitude suitable for production rises from 600 to 1000 m.a.s.l.
	Kenya	2.3ºC increase in temperature Rainfall increase from 1405mm to 1575 mm	Substantial decline in suitability of western highlands, some decline in area optimal for production in eastern highlands	Minimum altitude for production rise from 1000 to 1400 m.a.sl.
Tea	Kenya	2.3ºC increase in temperature Rainfall increase from 1655mm to 1732 mm	Majority of western highlands loose suitability, while looses are compensated by gains at higher altitude in eastern highlands	Optimum altitude for production change from 1500-2100 m.a.s.l. to 2000-2300 m.a.s.l.
	Uganda	2.3ºC increase in temperature Rainfall increase from 1334mm to 1394 mm	Considerable reduction in suitability for production across all areas	Optimal altitude change from 1450-1650 m.a.s.l. to 1550-1650 m.a.s.l.
Cocoa	Ghana, Ivory Coast	2.1ºC increase in temperature No change in total rainfall	Considerable reduction in area suitable for production; almost total elimination in Ivory Coast	Optimal altitude changes from 100-250 m.a.s.l. to 450-500 m.a.s.l.

Sources: CIAT, 2010; CIAT, 2011b; CIAT, 2011c; Laderach *et al.*, 2010

Table 9-5: Illustrative sample of studies on economic value and changes in value from climate change.

Study : Author /s	**Country / Region**	**Findings and Estimates**
Vaghefi *et al*., 2011	Malaysia (2 degrees C rise in temperature)	Annual economic loss in rice production: $ 54.17 million
Zhai and Zhuang, 2009	South East Asian countries : Thailand, Vietnam, Philippines	GDP reduction from loss of agricultural productivity by 2080: 1.7-2.4%
Guiteras, 2007	India	GDP reduction from agricultural losses: 1-1.8% Consumption reduction for poor: 18%
ADB and IFPRI, 2009	Asia	Annually spending for coping with adverse agricultural impacts between 2010-2050: $4.2 - $ 5 billion
Mendelsohn *et al*., 2010	Mexico	Decline in farmland values for each degree of warming: 4-6000 pesos
Mendelsohn *et al*., 2007	U.S. A. (10% average increase in temperature)	Fall in crop land values for rural communities: 13%
Mendelsohn and Reinsborough, 2007	Canada (increasing precipitation) U.S.A. (increasing temperature)	Mixed effects with some improved profits Adverse impacts on farming
Wittrock *et al*., 2011	Canada (Canadian Global Model 2)	Crop losses under drought: CAN$ 7-171 per hectare
Franco *et al*., 2011	California (B1 – low emissions and A2 – medium emissions scenarios)	Annual Agricultural losses upto $3billion Flooding increases losses
World Bank, 2010a	Mozambique (Dynamic CGE model)	Damages to agriculture, hydropower and infrastructure (including coastal areas) by 2050: $7.6 billion
Mideksa, 2010	Ethiopia (Cline, CGCM2 and PCM)	Decline in GDP from agriculture and linked sectors: 10% from benchmark levels
Dinar *et al*., 2008	11 African countries (Ricardian analysis; various climate scenarios)	By 2100: Total losses of $48.2 billion to gains of $ 90 billion In 2020 for 1.6% warmer and 3.7% dryer climate: net farm revenues decline by upto 25%
Nelson *et al*., 2009	Africa (A2 scenario; CSIRO and NCAR models)	Food security impacts Decline in calore consumption per capita per day by: 500 calories
Schlenker and Roberts, 2010	Africa (A1B scenario; WCRP CMIP3)	Losses for crops except Cassava: likelihood of 95% that losses exceed 7% 5% probability that losses exceed 27%
ECLAC, 2010a, b	Guatemala, Belize, Costa Rica, Honduras (SRES A2 and B2; Regional climate models)	Losses in gross value of production upto 25% (Guatemala, followed by other countries)
Seo and Mendelsohn, 2008	South America (SRES A1; Canadian Climate Centre)	Loss in incomes of farmers by: 2020: 14% 2060: 20%
Sanghi and Mendelsohn, 2008	Brazil (Climate predictions from 14 GCMs)	Annual damages between: 1 – 39%
Fallon and Betts, 2010	Southern Europe (2 degrees C rise in temperature)	Increased costs of agricultural production
Olesena *et al*., 2011	Hungary, Serbia, Bulgaria, Romania	Negative impacts for crops in continental climatic zone

Table 9-6: Examples of adaptations in the agricultural sector in different regions.

Agricultural adaptations	**Where it has been observed and source**
Modifying planting, harvesting and fertilising practices for crops	Anchioreta in Brazil (Bonatti et al., 2012), semi-arid mountain regions of Bolivia (PNCC, 2007), Chile (Meza and Silva, 2009), maize and wheat crops in Argentina (Magrin et al., 2009; Travasso et al., 2009b), South Africa and Ethiopia (Bryan *et al*, 2009), composting and coraaling of livestock to collect waste in northern Burkino Faso (Barbier et al, 2009), Sahelian region of Mali (Adepetu and Berthe, 2007), in North West Province, Limpopo Province and KwaZulu Natal, South Africa (Thomas *et al*, 2007)
Changing amount or area of land under cultivation	Moving winter wheat northwards and expanding rice crops (Lin et al., 2005), South Africa (Bryan et al, 2009), expansion of fields in northern Burkino Faso (Barbier et al, 2009), increase in the size of plots in the Sahelian region of Mali (Adepetu and Berthe, 2007)
Using different varieties (e.g. early maturing, drought-resistant)	Early maturing cultivars in South Brazil (Walter et al, 2010), North America (Coles and Scott, 2009), drought-tolerant in Asia (Thomas, 2008; Zhao et al., 2010), South Africa and Ethiopia (Bryan *et al,* 2009), Ghana (Gyampoh et al, 2008), northern Burkino Faso (Barbier et al, 2009), Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), in North West Province, Limpopo Province and KwaZulu Natal, South Africa (Thomas *et al*, 2007)
Diversifying crops	Peruvian Andes (Lin, 2011), South America (Montenegro and Ragrab, 2010), northeastern Mexico (Eakin and Appendini, 2008; Eakin and Bojorquez-Tapia, 2008), Tasmania, Australia (Smart, 2010), in KwaZulu Natal, South Africa (Thomas et al, 2007)
Commercialisation of agriculture	Income generation from natural resources (e.g. fuelwood) in the Limpopo River Basin, Botswana (Dube and Sekhela, 2007), Ghana (Gyampoh *et al*, 2008), Limpopo Province, South Africa (Thomas et al, 2007)
Water control mechanisms (including irrigation and water allocation rights)	Improved rice harvests in monsoonal Asia (Hatcho et al., 2010); adaptation for quinoa (Bolivian Altiplano), tomatoes (central Brazil) and cotton (northern Argentina (Geerts and Raes, 2009); for rice in northeast China (Lin et al, 2005); small water harvesting pits (known as zai) in improved yields and incomes due to improved soil moisture in Ethiopia (Amede *et al*., 2011; Bryan *et al*, 2009) and Burkina Faso (Hertsgaard, 2011, Barbier *et al*, 2009), in South Africa (Bryan et al, 2009), amongst rural women farmers in the Eastern Cape, South Africa (Bryan *et al*, 2009), Ghana (Gyampoh et al, 2008), dry season vegetable production through irrigation in northern Burkino Faso to enable two crop cycles (Barbier et al, 2009), Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), in Limpopo Province, South Africa (Thomas et al, 2007)
Shading and wind breaks	For coffee in Brazil, Costa Rica and Colombia (Camargo, 2010), Ethiopia (Bryan *et al,* 2009)
Conservation agriculture (e.g. soil protection, agroforestry)	Honduras, Nicaragua and Guatemala (Holt-Gimenez, 2002), Burkina Faso (Hertsgaard, 2011, Barbier *et al*, 2009), Ethiopia (Bryan *et al*, 2009), Sahelian region of Mali (Adepetu and Berthe, 2007)
Modifying grazing patterns for herds	Arctic (Bartsch et al, 2010), East Africa (Eriksen and Lind, 2009) and southern Africa (O'Farrell *et al*., 2009), moving livestock to less densely populated pastures in northern Burkino Faso (Barbier et al, 2009) and the Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), in North West Province, Limpopo Province and KwaZulu Natal, South Africa (Thomas *et al*, 2007)
Providing supplemental feeding for herds/ storage of animal feed	Arctic (P. and M., 2008; Forbes and Kumpula, 2009), South Africa (Bryan *et al*, 2009), use of sorghum and hay residue for feeding livestock in northern Burkino Faso (Barbier et al, 2009), Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), cutting fodder for livestock in Limpopo Province, South Africa (Thomas *et al*, 2007)
Ensuring optimal herd size	Arctic (Forbes et al, 2009), culling of livestock in Northern Nigeria (Adepetu and Berthe, 2007), selling of livestock northern Burkino Faso (Barbier et al, 2009) and the Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007)
Developing new crop and livestock varieties (e.g. biotechnology and breeding)	Brazil and Argentina (Marshall, 2012; Urcola et al, 2010), Northern Nigeria (Adepetu and Berthe, 2007)

Table 9-7: Examples of adaptations in the water sector observed in different regions.

Type	Example	Where it has been observed and source
Supply-side mechanisms	Dams	Proposed in the Volta River in Ghana (van de Giesen *et al*., 2010).
	Reservoirs	Asia (Tyler and Fajber, 2009), particularly in areas where water stress is an issue of distribution rather than absolute shortage (Biemans et al, 2011; Rivera-Ferre et al 2013)
	Groundwater pumping	Arid and semi-arid South America (Burte et al., 2011; Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010)
	Groundwater recharge	Potential identified in India (Sukhija, 2008)
	Irrigation (often using water-saving technology)	Asia (Ngoundo et al., 2007; Tischbein etal., 2011)
	Fog interception practices	South America (Holder, 2006; Klemm et al., 2012)
	Water capture	Bolivia (PNCC, 2007)
Demand-side mechanisms	Improved management, e.g. through efficiency	Asia (Kranz et al, 2010), South America (Bell et al., 2011; Geerts et al., 2010; Montenegro and Ragab, 2010; Van Oel et al., 2010); Pampas Argentina (Quiroga and Gaggioli, 2011)
	Policies	Murray-Darling Basin Authority (MDBA) established to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011) See also box 26-3 on Australia's water policies;
	Reviewing allocation rights	Indogangetic Plains (Rivera-Ferre et al., 2013); Australia's MDBA reviewed the "exceptional circumstances" concept in drought policy (Productivity Commission, 2009);

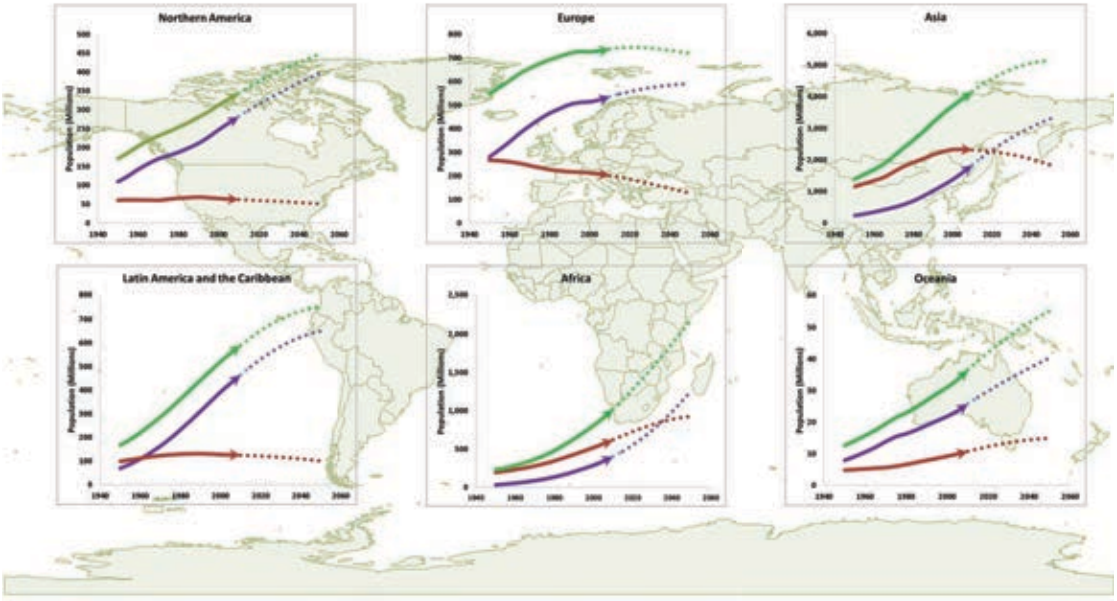

Figure 9-1: Trends in rural (red), urban (purple), and total (green) populations by region. Solid lines represent observed values and dotted lines represent projections. Source: United Nations, Department of Economic and Social Affairs/Population Division (2012).

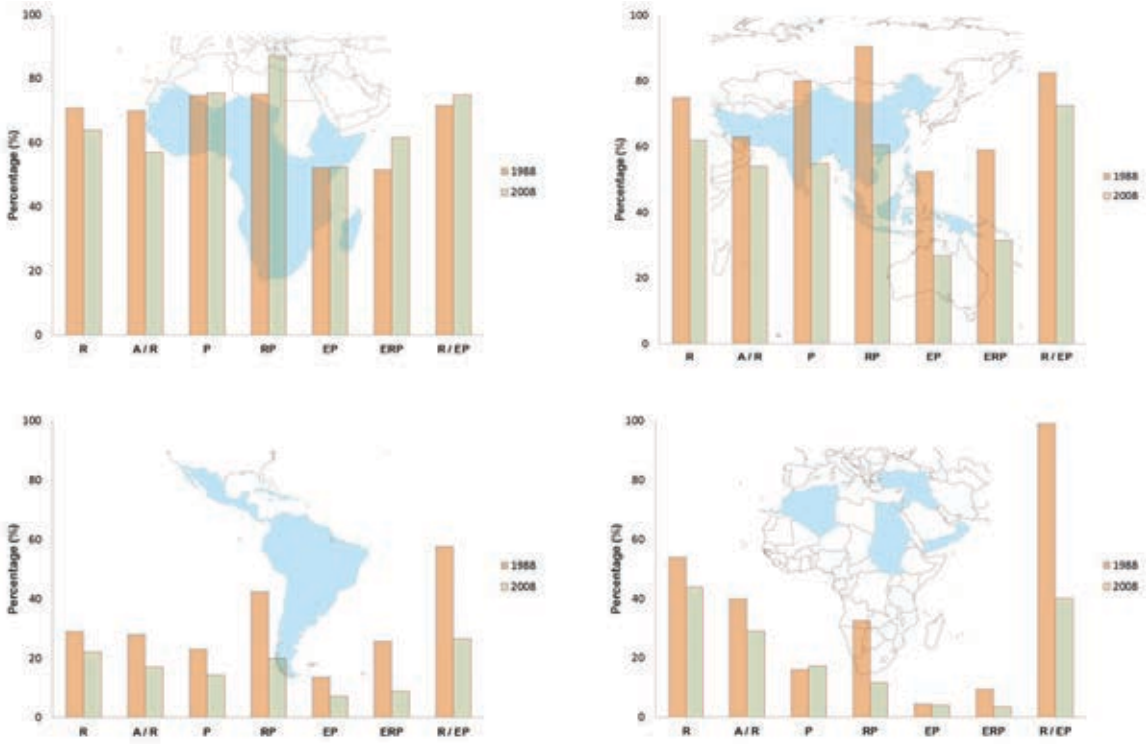

Figure 9-2: Demographic and poverty indicators for rural areas of developing countries, by region. R: percentage of rural population; A/R: agriculture as percentage of rural; P: incidence of poverty; RP: incidence of rural poverty; EP: incidence of extreme poverty; ERP: incidence of extreme rural poverty; R/EP : rural as percentage of those in extreme poverty. Source: Adapted from IFAD (2011).

10. Key Economic Sectors and Services

Coordinating Lead Authors
Douglas Arent (USA), Richard S.J. Tol (UK / The Netherlands)

Lead Authors
Eberhard Faust (Germany), Joseph P. Hella (Tanzania), Surender Kumar (India), Kenneth M. Strzepek (UNU / USA), Ferenc L. Toth (IAEA / Hungary), Denghua Yan (China)

Contributing Authors
Francesco Bosello (Italy), Paul Chinowsky (USA), Kristie L. Ebi (USA), Stephane Hallegatte (France), Philip Ward ( ), Eric Williams ( )

Review Editors
Amjad Abdullah (Maldives), Haroon Kheshgi (USA), He Xu (China)

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CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

Appendix
10.A1. Industrial Classification and Chapter Outline

References

Executive Summary

Climate change would reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*high agreement, robust evidence*); the balance of the two depends on the geographic, socioeconomic and technological conditions. Increasing income will allow people to regulate indoor temperatures to a comfort level that leads to fast growing energy demand for air conditioning even in the absence of climate change in warm regions with low income levels at present. Energy demand will be influenced by changes in demographics (upwards by increasing population and decreasing average household size), lifestyles (upwards by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices and the abundance and energy efficiency of other electric household appliances. The relative importance of these drivers varies across regions and will change over time. [10.2]

Climate change would affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling) or the locations (coastal regions, floodplains) involved (*high agreement, robust evidence*). Gradual changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) and possible changes in the frequency and intensity of extreme weather events will progressively affect operation over time. Climate-induced changes in the availability and temperature of water for cooling are the main concern for thermal and nuclear power plants, but several options are available to cope with reduced water availability. Similarly, already available or newly developed technological solutions allow firms to reduce the vulnerability of new structures and enhance the climate suitability of existing energy installations. [10.2]

Climate change would influence the integrity and reliability of pipelines and electricity grids (*medium agreement, medium evidence*). Pipelines and electric transmission lines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Climate change is *about as likely as not* to require the adoption of technological solutions for the construction and operation of pipelines and power transmission and distribution lines from other geographical and climatic conditions, adjustments in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions. [10.2]

Climate change would have impacts, heterogeneous in both sign and size, on water resources and water use (*high agreement, robust evidence*), but the economic implications are not well understood. Economic impacts include flooding, scarcity and cross sectoral competition. Flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Water scarcity and competition for water, driven by institutional, economic or social factors, may mean that water assumed to be available for a sector is not. [10.3]

Climate change would negatively affect transport infrastructure (*high agreement, limited evidence*). Transport infrastructure malfunctions if the weather is outside the design range, which would happen more frequently should climate change. All infrastructure is vulnerable to freeze-thaw cycles and paved roads are particularly vulnerable to temperature extremes, unpaved roads to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.4]

Climate change would affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (high agreement, robust evidence) and tourists would be inclined to spend their holidays at higher altitudes and latitudes (*high agreement, medium evidence*). The economic implications of climate-change-induced changes in tourism demand and supply may be substantial, with gains for countries closer to the poles and higher up the mountains and losses for other countries. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically and seasonally. [10.6]

Climate change strongly affects insurance systems (*high agreement, robust evidence*). More frequent and/or intensive weather disasters increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. Large-scale public-private risk prevention

initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially resilient insurance systems. [10.7]

Climate change would affect the health sector (*high agreement, medium evidence*) through increases in the frequency, intensity, and extent of extreme weather events adversely affecting infrastructure and increase the demands for services due to the human health impacts of climate change, placing additional burdens on public health, disease burden, and health care personnel and supplies; these have economic consequences. [10.8]

Markets provide an additional mechanism for adaptation and would thus reduce negative impacts and increase positive ones for any specific sector or country (*high agreement, medium evidence*). The impacts of climate on one sector of the economy of one country in turn affect other sectors and other countries though product and input markets. Markets increase overall welfare, but not necessarily welfare in every sector and country. [10.9]

The impacts of climate change would decrease productivity and economic growth, but the magnitude of this effect is not well understood (*high agreement, limited evidence*). Climate could be one of the causes why some countries are trapped in poverty, and climate change may make it harder to escape poverty traps. [10.9]

Not all key sectors have been subject to detailed research based on a comprehensive assessment across economic sectors. Few studies have evaluated the possible impacts of climate change on mining, manufacturing or services (apart from health, insurance and tourism).Further research, collection and access to more detailed economic data and the advancement of analytic methods and tools will be required to further assess the potential impacts of climate on key economic systems and sectors. [10.5, 10.8, 10.10]

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services; e.g., economic activity. Other chapters discuss impacts from a physical, chemical, biological, or social perspective. Economic impacts cannot be isolated; and therefore, there are a large number of cross-references to other chapters in this report. In some cases, particularly agriculture, the discussion of the economic impacts is integrated with the other impacts.

Focusing on the potential impact of climate change on economic activity, this chapter addresses questions such as: how does climate change affect the demand for a particular good or service? What is the impact on its supply? How do supply and demand interact in the market? What are the effects on producers and consumers?

An inclusive approach was taken, discussing all sectors of the economy. Appendix A shows the list of sectors according to the International Standard Industrial Classification. This assessment reflects the breadth and depth of the state of knowledge across these sectors; many of which have not been evaluated in the literature. We extensively discuss five sectors: Energy (10.2), water (10.3), transport (10.4), tourism (10.6), and insurance (10.7). Other primary and secondary sectors are discussed in 10.5, and 10.8 is devoted to other service sectors. Food and agriculture is addressed in Chapter 7. Sections 10.2 through 10.8 discuss individual sectors in isolation. Markets are connected, however. Section 10.9 therefore assesses the implications of changes in any one sector on the rest of the economy. It also discusses the effect of the impacts of climate change on economic growth and development. Chapter 19 assesses the impact of climate change on economic welfare – that is, the sum of changes in consumer and producer surplus, including for goods and services not traded within the formal economy. This is not attempted here. The focus is on economic activity. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

Previous assessment reports by the IPCC did not have a chapter on “key economic sectors and services”. Instead, the material assembled here was spread over a number of chapters. AR4 is referred to in the context of the sections below. In some cases, however, the literature is so new that previous IPCC reports did not discuss these impacts at any length.

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy demand as reported in the SAR (Acosta Moreno *et al*., 1995) and reinforced by the TAR (Scott *et al.*, 2001) and AR4 (Wilbanks *et al.*, 2007): ceteris paribus, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographic, socioeconomic and technological conditions. The relative importance of temperature changes among the drivers of energy demand varies across regions and will change over time. Earlier IPCC assessments did not write much about energy supply, but an increasing number of studies now explore its vulnerability, impacts and the adaptation options (Troccoli, 2010); (Ebinger and Vergara, 2011); (USGCRP, 2009). The energy sector will be transformed by climate policy (Bashmakov et al., forthcoming) but impacts of climate changes too will be important for secure and reliable energy supply.

10.2.1. Energy Demand

Most studies conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity. Some studies encompass the commercial sector as well but very few deal with industry and agriculture. In addition to a few global studies based on global energy or integrated assessment models, the new studies tend to focus on specific countries or regions, rely on improved methods (more advanced statistical techniques) and data (both historical and regional climate projections), and many of them explicitly include non-climatic drivers of energy demand. A few studies consider changes in demand together with changes in climate-dependent energy sources, like hydropower.

Figure 10-1 sorts the assessed studies according to the present climate (represented by mean annual temperature) and current income (represented by GDP per capita). Neither indicator is ideal: country-level mean annual temperatures for large countries can hide large regional differences and average incomes may conceal large disparities, but they help cluster the national and regional studies in the search for general findings (Toth, 2013).

[INSERT FIGURE 10-1 HERE
Figure 10-1: GDP per capita (in 2009) and annual mean temperature (based on 1971-2000 climatology) in selected countries and US federal states. Source: Toth, 2013.]

The general patterns are (i) in countries and regions with already high incomes, climate-related changes in energy demand will be primarily driven by increasing temperatures, with associated heavier use of air-conditioning in warm climates, and (ii) lower demands for various energy forms (electricity, gas, coal, oil) in temperate and cold climates, while increasing incomes will play a marginal role. In contrast, changes in income will be the main driver of increasing demand for energy (mainly electricity for air conditioning and transportation fuels) in present-day low-income countries in warm climates.

At the global scale, energy demand for residential air conditioning in summer is projected to increase rapidly in the 21st century under the reference climate change scenario (medium population and economic growth globally, but faster economic growth in developing countries; no mitigation policies in addition to those in place in 2008) by the TIMER/IMAGE model (Isaac and Van Vuuren, 2009). The increase is from nearly 300 TWh in 2000, to about 4,000 TWh in 2050 and more than 10,000 TWh in 2100, about 75% of which is due to increasing income in emerging market countries and 25% is due to climate change. Energy demand for heating in winter increases too, but much less rapidly, since in most regions with the highest need for heating, incomes are already high enough for people to heat their homes to the desired comfort level (except in some poor households). In these regions, energy demand for heating will decrease.

These general patterns and especially the quantitative results of the projected shifts in energy and electricity demand can be modified by many other factors. In addition to changes in temperatures and incomes, the actual energy

demand will be influenced by changes in demographics (upwards by increasing population and decreasing average household size), lifestyles (upwards by larger floor area of dwellings), the design and insulation of the housing stock, the energy efficiency of heating/cooling devices, the abundance and energy efficiency of other selectric household appliances, the price of energy, etc.

10.2.2. Energy Supply

Changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change (CC) will progressively affect operation over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) represent a different kind of hazard for energy installations and infrastructure. This section assesses the most important impacts and adaptation options in both categories. Table 10-1 provides an overview.

[INSERT TABLE 10-1 HERE
Table 10-1: Main projected impacts of CC and EWEs on energy supply.]

Currently, thermal power plants provide about 80% of global electricity and their share is projected to remain high in most mitigation scenarios (IEA, 2010aa). Thermal power plants are operated under diverse climatic conditions from the cold Arctic to the hot tropical regions and are well adapted to the prevailing conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change.

The most significant impact of CC on thermal power generation is the decreasing efficiency of thermal conversion as a result of rising temperature. This follows from Carnot's rule and cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2012), supercritical and ultra-supercritical steam-cycle plants will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures. Yet in the absence of CC, these efficiency gains from improved technology would reduce the costs of energy, so there is still a net economic loss due to CC. Another problem facing thermal power generation in many regions is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity and even temporary shutdown of power plants (Ott and Richter, 2008; Hoffmann *et al.*, 2010; IEA, 2012; Nee Schulz, 2012). Both problems will be exacerbated if CO_2 capture and handling equipment is added to fossil-fired power plants: energy efficiency declines by 8-14 % and water requirement per MWh electricity generated can double (IPCC, 2005).

Adaptation possibilities range from relatively simple and low-cost options like exploiting non-traditional water sources and re-using process water to measures like installing dry cooling towers, heat pipe exchangers and regenerative cooling (Ott and Richter, 2008; De Bruin *et al.*, 2009), all which increase costs. While it is easier to plan for changing climatic conditions and select the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those towards the end of their economic lifetime.

CC impacts on thermal efficiency and cooling water availability affect nuclear power plants similarly to their thermal counterparts (Williams and Toth, 2013). Whereas there is no escape from Carnot's rule affecting efficiency, a range of alternative cooling options are available to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III *et al.*, 2008) to installing dry cooling (EPA , 2001).

The implications of EWEs for nuclear plants can be severe if not properly addressed. Reliable interconnection (onsite power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) is indispensable for the safe operation and/or shutdown of a nuclear reactor. For most of the existing global nuclear fleet, a reliable connection to the grid for power to run cooling systems and control instruments in emergency situations is another crucial item (IAEA (International Atomic Energy Agency), 2011). Several EWEs can damage the components or disrupt their interconnections. Preventive and protective

measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown) (Williams and Toth, 2013).

Hydropower is by far the largest of renewable energy sources in the current energy mix. It is projected to remain important in the future, irrespective of the climate change mitigation targets in many countries (IEA, 2010aa; IEA, 2010b). The resource base of hydropower is the hydrologic cycle driven by prevailing climate and topology. The former makes the resource base and hence hydropower generation highly dependent on future changes in climate and related changes in extreme weather events (Ebinger and Vergara, 2011; Mukheibir, 2013).

Assessing the impacts of climate change on hydropower generation is the most complex endeavour in the energy sector. A series of non-linear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation make resource estimates difficult (see Chapters 2 and 3) while regional changes in water demand due to changes in population, economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regime.

Focusing on the possible impacts of CC on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, the seasonal and inter-annual variations of available water, and in other demands, the overall conclusion from the literature is that the impacts of CC and EWEs on hydropower generation is *likely* to increase in most regions and decrease in some, with diverging patterns across regions, watersheds within regions and even river basins within watersheds. Planning tools for long-term hydrogeneration may need to be enhanced to cope with slow but persistent shifts in water availability, and short-term management models may need to be enhanced to deal with the impacts of EWEs. A series of hard (raising dam walls, adding bypass channels) and soft (adjusting water release) measures are available to protect the related infrastructure (dams, channels, turbines, etc.) and optimize incomes by timing generation when electricity prices are high (Mukheibir, 2013).

Solar energy is expected to increase from its currently small share in the global energy balance across a wide range of mitigation scenarios (IEA, 2008; IEA, 2010aa; IEA, 2010ab; IEA, 2010ab; IEA, 2010b). The three main types of technologies for harnessing energy from insolation include thermal heating (TH) (by flat plate, evacuated tube and unglazed collectors), photovoltaic (PV) cells (crystalline silicon and thin film technologies) and concentrating solar power (CSP) (power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to CC and EWEs is reviewed by (Patt *et al.*, 2013).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. If cloudiness increases under climate change (see Chapters 11 and 12 of the WGI report), the intensity of solar radiation and hence the output of heat or electricity would be reduced. Efficiency losses in cloudy conditions are less for technologies that can operate with diffuse light (evacuated tube collectors for TH, PV collectors with rough surface). Since diffuse light cannot be concentrated, CSP output would cease under cloudy conditions but the easy and relatively inexpensive possibility to store heat reduces this vulnerability if sufficient volume of heat storage is installed (Khosla, 2008; Richter *et al.*, 2009).

The exposure of sensitive material to harsh weather conditions is another source of vulnerability for all types of solar technologies. Windstorms can damage the mounting structures directly and the conversion units by flying debris, whereby technologies with smaller surface areas are less vulnerable. Hail can also cause material damage and thus reduced output and increased need for repair. Depending on regional conditions, strong wind can deposit sand and dust on the collectors' surface, reducing efficiency and increasing the need for cleaning.

CC and EWE hazards per se do not pose any particular constraints for the future deployment of solar technologies. Technological development continues in all three solar technologies towards new designs, models and materials. One of the objectives of these development efforts is to make new models less vulnerable to current climate and EWEs. Technological development also results in a diverse portfolio of models to choose from according to the

climatic and weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

Harnessing wind energy for power generation is an important part of the climate change mitigation portfolio in many countries. Assessing the possible impacts of CC and EWEs on this technology and exploring possible adaptation options are complicated by the complex dynamics characterizing wind energy. Relevant attributes of climate are expected to change; the technology is evolving (blade design, other components); see (Kong *et al.*, 2005; Barlas and Van Kuik, 2010); there is an increasing deployment offshore and a transition to larger turbines (Garvey, 2010) and to larger sites (multi megawatt arrays) (Barthelmie *et al.*, 2008).

The key question concerning the impacts of a changing climate regime on wind power is related to the resource base: how climate change will rearrange the temporal (inter- and intra-annual variability) and spatial (geographical distribution) characteristics of the wind resource. (Pryor and Barthelmie, 2010) find that in the next few decades wind resources (measured in terms of multi-annual wind power densities) are estimated to remain within the ±50% of the values compared to the past 20 year mean values. The wide range of the estimates results from the circulation and flow regimes in different GCMs and regional climate models (RCMs) (Bengtsson *et al.*, 2006; Pryor and Barthelmie, 2010). A set of four GCM-RCM combinations for the period 2041-2062 indicates that average annual mean energy density will be within ±25% of the 1979-2000 values in all 50 km grid cells over the contiguous USA (Pryor *et al.*, 2011(a); Pryor and Barthelmie, 2013). Yet, little is known about changes in the inter-annual, seasonal or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. As shown in Table 10-1, siting, design and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirements to withstand extreme loading conditions resulting from climate change are within the safety margins prescribed in the design standards, although load from combinations of extreme events may exceed the design thresholds (Pryor and Barthelmie, 2013). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

In the coal fuel cycle, vulnerability in mining depends on the mining method. Open cast mining might be particularly affected by high precipitation extremes and related floods and erosion, and temperature extremes, especially extreme cold that might encumber extraction for some time, whereas impacts on coal cleaning and operation of underground mines will probably be less severe. Changes in drainage and run-off regulation for on-site coal storage as well as in coal handling might be required due to the increased moisture content of coal and more energy might be required for coal drying before transportation (CCSP, 2007). Using current carbon dioxide capture technologies would almost double water consumption per unit of electricity generated from coal-fired plants, exacerbating water supply problems in water-stressed regions and/or seasons. At the back end of the fuel cycle, the management of fly-ash, bottom ash and boiler slag may need to be modified in response to changes in some EWE patterns like wind, precipitation and floods.

Climate and weather related hazards in the oil and gas sector include tropical cyclones with potentially severe effects on off-shore platforms and on-shore infrastructure as well, leading to more frequent production interruptions and evacuation (Cruz and Krausmann, 2013). Gradual changes in air temperature and precipitation are projected to generate risk and opportunities for the oil and gas industry. For example, reduced sea ice thickness and coverage might open new shipping routes, thus reducing shipping costs, while ice scour and ice pack loading on marine structures would increase. However, most changes involve increased risks, such as thawing permafrost would increase construction costs on unstable ground relative to ice-based construction, while thaw subsidence would trigger increased maintenance costs. Sea level rise and coastal erosion would degrade coastal barriers, damage facilities and trigger relocation (Dell and Pasteris, 2010).

10.2.3. Transport and Transmission of Energy

Primary energy sources (coal, oil, gas, uranium), secondary energy forms (electricity, hydrogen, warm water) and waste products (CO_2, coal ash, radioactive waste) are transported in diverse ways to distances ranging from a few to

thousands of kilometres. The transport of energy-related materials by ships (ocean and inland waters), rail and road are exposed to the same impacts of climate change as the rest of the transport sector (see Section 10.4). This subsection deals only with transport modes that are unique to the energy sector (power grid) or predominantly used by it (pipelines). Table 10-2 provides an overview of the impacts of CC and EWEs on energy transmission, together with the options to reduce vulnerability.

[INSERT TABLE 10-2 HERE
Table 10-2: Main impacts of CC and EWEs on pipelines and the electricity grid.]

Pipelines play a central role in the energy sector by transporting oil and gas from the wells to processing and distributing centres to distances from a few hundred to thousands of kilometres. With the spread of CO_2 capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically fossil power plants) to the disposal site onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet adjustments may be needed in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions.

Pipelines will be mainly affected by secondary impacts of climate change: sea-level rise in coastal regions, melting permafrost in cold regions, and floods and landslides triggered by heavy rainfall. A proposed way to reduce vulnerability to these events is the amendment of land zoning codes, and the design and construction standards for new pipelines and structural upgrade for existing ones (Antonioni *et al.*, 2009; Cruz and Krausmann, 2013).

Due to the very function of the electricity grid to transmit power from generation units to consumers, the bulk of its components (overhead lines, substations, transformers) are located outdoors and exposed to EWE. The power industry has developed numerous technical solutions and related standards to protect those assets and provide reliable electricity supply under prevailing climate and weather conditions worldwide; however, much existing infrastructure is vulnerable to EWEs.

Higher average temperatures decrease transmission efficiency by about 0.4%/°C but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2013). Historically, high wind conditions, including storms, hurricanes and tornados, have been the most frequent cause of grid disruptions (mainly due to damages to the distribution networks), and more than half of the damage was caused by trees (Reed, 2008). If the frequency and power of high wind conditions, as well as extreme precipitation events, will increase in the future, vegetation management along existing power lines and rerouting new transmission lines along roads or across open fields might help reduce related risks.

The economic importance of a reliable transmission and distribution network is highlighted by the fact that the damage to customers tend to be much higher than the price of electricity not delivered (lost production, electricity enabled commerce, service delivery, food spoilage, lost or restricted water availability). Designing and building climate-resilient infrastructure will depend on technical standards, market governance, and the type and degree of liberalization and deregulation of grid services.

10.2.4. Macroeconomic Impacts

Most economic research related to climate change impacts on the energy sector has focused on mitigation rather than the economic implications of climate change itself. Table 10-3 summarizes the recent studies on the economic implications of climate change and extreme weather impacts in the energy sector.

[INSERT TABLE 10-3 HERE
Table 10-3: Economy-wide implications of impacts of climate change and extreme weather on the energy sector.]

Assessing across a broad array of studies that focus on different regions and regional divisions, examine different climate change impacts, include a different mix of sectors, model different timeframes, make different assumptions about adaptation, and employ different types of models with different output metrics leads to the overall conclusion that the macroeconomic impact of climate change on energy demand is *likely* to be minimal in developed countries (Bosello *et al.*, 2007; Aaheim *et al.*, 2009; Bosello *et al.*, 2009; Jochem *et al.*, 2009; Jochem *et al.*, 2009; Eboli *et al.*, 2010a).

The current literature sheds less light on the implications for developing countries and on other climate impacts in the energy sector beyond those related to changes in energy demand. Europe is the focus of most of the literature so far. Asia, Africa, and Latin America are not well represented, appearing in only two global studies. The limited results indicate that developing countries *likely* face a greater negative GDP impact with respect to climate change implications for the energy sector than developed countries (Aaheim *et al.*, 2009; Boyd and Ibarraran, 2009; Eboli *et al.*, 2010a).

Despite the considerable number of potential climate change and extreme weather phenomena – higher mean temperatures, changes in rainfall patterns, changes in wind patterns, changes in cloud cover and average insolation, lightning, high winds, hail, sand storms and dust, extreme cold, extreme heat, floods, drought, and sea-level rise – and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, and energy demand (Williams, 2013) – the range of impacts modeled in the literature (Table 10-3) is quite limited. Most studies consider changing energy demand (specifically, changes in electricity and fuel consumption for space heating/cooling) resulting from rising temperatures as the only or primary climate change impact. These studies draw upon recent literature refining the relationship between climate change and energy demand: the demand for natural gas and oil in residential and commercial sectors tends to decline with climate change because of less need for space heating, and demand for electricity tends to increase because of greater need for space cooling (Gabrielsen *et al.*, 2005; Gabrielsen *et al.*, 2005; Kirkinen *et al.*, 2005; Mansur *et al.*, 2005; Gunnar and Torben, 2010; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

Studies using a computable general equilibrium (CGE) model that consider only climate impacts in the energy sector find that the effect on GDP in 2050 is quite modest at -0.3% to 0.03% (Bosello et al. 2007) and -1.3% to -0.6% (Jochem *et al.*, 2009). These findings are largely consistent despite the fact that (Bosello *et al.*, 2007; Bosello *et al.*, 2009) are global studies that model only the change in demand due to rising temperatures, whereas (Jochem *et al.*, 2009) focus on the EU and model the change in demand plus six other climate impacts.

Studies using CGE models that examine the aggregate changes in GDP brought on by climate impacts in energy and several other sectors have also primarily found moderate shifts in GDP. (Aaheim *et al.*, 2009) conclude that in 2100 in cooler regions in the EU, GDP changes by -1% to -0.25% and in warmer regions changes by -3% to -0.5%. (Boyd and Ibarraran, 2009) project a -3% change in GDP in 2026 for Mexico, consistent with the warmer regions modeled by (Aaheim *et al.*, 2009). Roughly consistent with each other (Aaheim *et al.*, 2009; Eboli *et al.*, 2010a) find GDP impacts for the predominantly cooler regions of Japan, the EU, EEFSU, and Rest of Annex I as having a "significant positive impact", while the predominantly warmer regions of the USA, EEx (China/India, Middle East/Most of Africa/Mexico/parts of Latin America), and the Rest of the World have a "significantly negative impact." (Jorgenson *et al.*, 2004) find that overall GDP impacts are -0.6% to 0.7% in 2050 for the United States, which stands in contrast to (Eboli *et al.*, 2010a) with a "significantly negative impact" in the United States.

Several CGE studies attempt to evaluate how adaptation changes in the energy sector impact GDP but do not examine specific adaptation options since CGE models lack the necessary technological detail. They make general assumptions about the effectiveness of adaptation policy in reducing climate impacts. (Jorgenson *et al.*, 2004) find that pessimistic assumptions about adaptation imply a 0.6% reduction in GDP in 2050 but optimistic assumptions lead to a 0.7% gain in GDP. (Aaheim *et al.*, 2009) conclude that adaptation can mitigate the costs of climate change by 80% to 85%, and (Boyd and Ibarraran, 2009) find that adaptation can shift a 3% GDP loss in 2026 in Mexico to a gain in GDP of 0.33%.

Partial equilibrium models, by their nature, do not have a full macroeconomic representation and therefore rarely report changes in GDP. Instead, these models focus on details in the energy sector, such as price and quantity effects

for fuels and electricity (and the mix of generation). (Golombek *et al.*, 2011) report a 1% increase in the price of electricity for Western Europe in 2030 stemming from rising temperatures that affect demand and thermal efficiency of supply, as well as water inflow. (Gabrielsen *et al.*, 2005) conclude that for Nordic countries in 2040, as a result of rising temperatures that affect demand, changes in water inflow, and changes in wind speeds, the price of electricity will decline by 1%. Although the change in price differs in sign, the magnitude of change is small in both studies. In contrast, (Bye *et al.*, 2006) in looking at a hypothetical water shortage scenario in Nordic countries, conclude that the price of electricity can double over a 2 year period and then return to normal as water flow returns. (DOE, 2009) also finds that a drought scenario can lead to average monthly electricity prices that are 8.1% (November) to 24.1% (July) higher. In contrast to the significant price impacts found by (Bye *et al.*, 2006) and (DOE, 2009), (Koch *et al.*, 2012) conclude that thermal plant outages in Berlin resulting from heat wave-driven water temperatures that exceed regulatory limits can amount to a cumulative cost of 60 million EURO over the period 2010 through 2050 for 2850 MW of capacity. Assuming an 80% capacity factor, the premium for high water temperatures in Berlin is 0.075 EURO per MWh.

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will *likely* increase the demand for energy in most regions of the world. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear and solar power generation, the potential and dependability of hydropower, etc. However, temperature-induced impacts on energy supply will probably make a relatively small contribution to the overall increase in demand for energy and electricity. Similarly, CC impacts on energy supply will be part of an evolving picture dominated by technological development in the pursuit for safer, cheaper and more reliable energy sources and technologies as well as mitigation and adaptation response pathways.

Given the limitations in the literature, sweeping conclusions about results may be premature on macroeconomic implications. However, some narrow conclusions are possible. The change in GDP due to temperature-induced changes in energy demand – even if combined with other climate impacts – is relatively small in all of the studies. Ranging from -3% to 1.2%. (Jochem *et al.*, 2009) which is the most detailed and comprehensive study, report only a 1.3% drop in GDP in 2050 in Europe due to at least seven climate impacts in the energy sector. The GDP impact in warmer regions tends to be greater than in cooler regions, which benefit from less need for space cooling. Energy related economic impact for developing countries is anticipated to be negative, and positive in developed countries. Adaptation can lower the cost of climate change, but these results may be driven largely by assumption since specific policies have not been modeled. Results from some of the partial equilibrium models suggests that CGE modeling studies, which largely focus on changes in energy demand, may be neglecting some potentially costly impacts from extreme weather events like drought, which, if modeled, may lead to greater GDP impacts than reported thus far in the literature.

Much research is still needed to understand the implications of climate change and extreme weather on the energy sector and to identify cost-effective adaptation options. The best understood area is the implications of climate on energy demand. A comprehensive evaluation of a full range of supply-side climate change impacts and adaptation options for all aspects of energy infrastructure is needed. This information will help modelers make much better, empirically-based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options. Expanding research into developing countries is also much needed, as developing countries are more vulnerable to climate change impacts and probably face more significant economic implications.

10.3. Water

This section focuses on economic aspects of climate change in water related economic sectors. The biophysical water system, including infrastructure, is assessed in Chapter 3.

10.3.1. Water-Related Economic Losses

Between the 1950s and the 1990s, the annual economic losses from large extreme events, including floods and droughts, increased tenfold, with developing countries being hardest hit (Kabat *et al.*, 2003). Over the past few decades, flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide (Munich Re, 2005). The economic losses associated with floods worldwide have increased by a factor of five between the periods 1950-1980 and 1996-2005 (Kron and Berz, 2007). From 1990 to 1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1,000, and 22 floods with losses exceeding US$1 billion each (Kabat et al., 2003). Although these increases are primarily due to several non-climatic drivers, climatic factors are also partly responsible (Kundzewicz *et al.*, 2007). SREX Chapter 4 {{1867 IPCC 2012}} provides a comprehensive look at the impacts of extreme events on water suppl(IPCC, 2012)y and flooding at wide range of spatial scales.

Most of the studies examining the economic impacts of climate change on the water sector have been carried out at the local, national, or river-basin scale; and, the global distribution of such studies is skewed towards developed countries (Schreider *et al.*, 2000; Chen *et al.*, 2001; Middelkoop *et al.*, 2001b; Choi and Fisher, 2003; Hall *et al.*, 2005). In other studies, the economic impacts of climate variability on floods and droughts in developing countries were reported as substantial. For example, the cost to Kenya of the floods associated with the 1997/8 El Niño and the drought associated with the 1998-2000 La Niña, show a cost to the country of 11% and 16% of GDP, respectively (Mogaka *et al.*, 2006). Floods and droughts are estimated to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka *et al.*, 2006). For Ethiopia, economy-wide models incorporating hydrological variability show a drop in projected GDP growth by up to 38% compared to when hydrological variability is not included (World Bank, 2006). However, it is not hydrological variability per se that causes the problem, but rather a lack of the necessary capacity, infrastructure, and institutions to mitigate the impacts (Grey and Sadoff, 2007). Similarly, future flood damages will depend not only on changes in the climate regime, but also on settlement patterns, land use decisions, flood forecasting quality, warning and response systems, and other adaptive measures (Pielke and Downton, 2000; Changnon, 2005; Ward *et al.*, 2008). In many developing countries, water related impacts are *likely* to be more pronounced with climate change (Chapter 3) and associated economic costs can be expected to be more substantial in the future, holding all other factors constant.

The Association of British Insurers (ABI) estimated the financial costs of climate change using insurance catastrophe models in the UK and across Europe. They found that climate change could increase the annual cost of flooding in the UK almost 15-fold by the 2080s under high emission scenarios. If climate change increased European flood losses by a similar magnitude, they estimate that costs could increase by up to $120-150 billion, for the same high emission scenarios (ABI, 2005). (Feyen *et al.*, 2012) project average annual damage in the EU to increase to Euro14-21.5 billion by 2100 depending on the scenario, compared to Euro6.4 billion today. Wobus et al., 2013, estimate an increase in continental US mean annual flood damages of $5 billion and $12 billion in 2050 and 2100, respectively.(Ntelekos *et al.*, 2010) estimate a range of $7-19 billion, depending on the economic growth rate and the emissions scenarios. Dasgupta et al report that by 2050 Bangladesh will face incremental cost to flood protection (against both sea and river floods) of $2.6 billion initial costs and $54 million annual recurring costs. (Ward *et al.*, 2008) found that the average annual costs to adapt to a 1in 50 year river flood to range from $3.5 to $6.0 billion per year for low- to upper-middle-income countries over the period 2010–50 for the A2 scenario.

10.3.2. Municipal and Industrial Water Supply

Beyond flood and other extreme event damages, municipal and industrial water supply economic systems are also impacted through anticipated changes in precipitation patterns and quantities. Economically, these impacts are evaluated as current costs of building in resiliency to the system to adapt to anticipated future changes. For example, the costs of adaptation to maintain supply and quality of water for municipal and industrial uses have been reported for the Assabet River near Boston (Kirshen *et al.*, 2006), Toronto (Dore and Burton, 2001) and Quito (Vergara *et al.*, 2007). Since much of this infrastructure has an economic and engineering life of less than 25 years, building flexibility into these systems is in most cases the best action now. (Nassopoulos *et al.*, 2012) suggest that neglecting to account for future climate change while designing water supply reservoirs can cost 0.2 to 2.8% of the net present

value, based on analysis for Greece. For sub-Saharan Africa, adapting urban water infrastructure (storage facilities, wastewater, and additional supply infrastructure) to a 30% reduction in runoff could be $2-5 billion per year (Muller, 2007). Climate change impacts on the Berg River in South Africa are estimated to account for 15% revenue loss for the water supply provider (Callaway et al 2012). For the OECD, the cost of adaption in the water supply sector is 1-2% of base costs and would save $6-12 billion per year (Hughes *et al.*, 2010). U.S. impacts are estimated to be less than 1% of municipal and industrial welfare (Hurd *et al.*, 2004) (Strzepek et al. 2013). In Colorado, a 30% decrease in annual runoff will result in a 12% treatment cost increase and a 22% rise in residential costs (Towler et al, 2011).

On a global scale, (Ward *et al.*, 2010) estimate the adaptation costs to provide enough raw water to meet future global industrial and municipal water demand, based on country-level demand projections to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs are estimated to be US$12B/yr (on top of US$73B/yr to meet the needs of development), with 83-90% in developing countries; the highest costs are in Sub Saharan Africa, and may be as high has 16% of total global adaptation costs. The global cost estimates of climate-change related adaptation in the water resources sector amount to 0.04–0.06 percent of world GDP. Adding resilient adaptive measures to water infrastructure adds 10-20% to the total costs of developing countries meeting the water related millennium goals which is estimated to be only 0.33 percent of GDP, but may help avoid future economic losses. .

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often, and increased occurrences of low flows will lead to higher pollutant concentrations. While no studies have been conducted on the potential economic losses associated with these systems, estimates of the annual costs of adaptation have been reported. For example, for urban sewers, average over 17 climate models, is $3.0 billion per year in low- to upper-middle-income nations over the period 2010–50 for the A2 scenario (Hughes *et al.*, 2010). Similarly, the cost of building and maintaining additional storm water storage capacity in Canada necessary to manage a 100-year, 24-hour storm is $0.1-2 billion present value for 2010-2100 with a 3% discount rate (Price et al. 2010). Adaptation costs estimates (for a 10-year, 24-hour storm in 2100) for various locations in the USA are relatively low; e.g., $135 million for Los Angeles, $7 million for Boston and $40 million for Chicago (Neumann et al 2013). Bridges are also vulnerable to flood damage, and (Wright *et al.*, 2012) estimate adaptation costs of $140-250 billion in the USA through the 21st century.

10.3.4. Energy: Hydropower and Cooling Water

Using partial equilibrium river basin models, (Hurd *et al.*, 2004) (Strzepek et al. 2013) estimate USA welfare loses due thermal cooling water changes at $622 million per year up to 2100, a 6.5 % welfare loss in the energy sector. (Van Vliet *et al.*, 2012) find that the southeastern United States, Europe, eastern China, southern Africa and southern Australia could potentially be affected by reduced water available for thermoelectric power and drinking water, inducing changes to dry or hybrid cooling (with concomitant loss in electric output), or plant shut downs, with associated impacts on local and regional economic activity. For hydropower locations, adaption to climate change to maintain output has been reported; in Ethiopia, (Block and Strzepek, 2012) report that capital expenditures through 2050 may either decrease by ~3% under extreme wet scenarios, or increase by up to 4% under a severe dry scenario. In the Zambezi river basin, hydropower falls by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek et al 2012). Lower generation is *likely* in the upstream powerstations of the Zambezi basin and increases are *likely* downstream (Fant *et al.*, 2012).

10.3.5. Inland Navigation

See 10.4.4.

10.3.6. Irrigation

Climate change impacts on the economics of irrigation reflect the anticipated change in temperature, precipitation, and agricultural demand and practices. These narrowly focused reports do not address the broader issues of food production (covered in Chapter 7), nor economy wide impacts (Chapter 19). For example, by 2080, the global annual costs of additional irrigation water withdrawals for currently existing irrigated land are estimated at $24-27 billion (Fischer et al 2007). The global cost of improved irrigation efficiency to maintain yields is $1.5-2.0 billion dollar per year in developing countries in 2050 for the A2 scenario. (Nelson *et al.*, 2009) find that adaptation for Ethiopia to maintain agricultural production in Ethiopia would be best achieved by soil water management from increased irrigated and drained areas, improved irrigation efficiency and research related to on-farm practices. Adaptation costs range from $68 million per year for the dry scenario dominated by irrigation, to $71 million per year under the wet scenario dominated by drainage (Strzepek et al. 2010).

10.3.7. Nature Conservation

Climate change is expected to worsen many forms of water pollution, including the load of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, increased precipitation intensity, and low flow periods (Kundzewicz *et al.*, 2007). Future water demands for nature conservation will be different than today's (see Chapter 4). There is no published assessment of the economic implications.

10.3.8. Recreation and Tourism

Tourism and recreation use substantial amounts of water but the implications of climate-change-induced changes in tourism and recreation on water demand have yet to be quantified. See Section 10.6.

10.3.9. Water Management and Allocation

Changes in water availability, demand and quality due to climate change would impact water management and allocation decisions. Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution(Adger *et al.*, 2007; UNFCCC, 2007). Water has been allocated based on societies' preferences. Under a changing climate, existing allocations may no longer be appropriate. Arndt et al 2012 examine the economy-wide implications of existing water allocations and alternative development paths and allocation to suggest climate-smart development strategies in Africa. Under stress situations, allocations of water for energy-generation and irrigation may have economy-wide welfare implications. Climate change impacts on undiscounted USA welfare over the 21st century range from plus $3 trillion for wet scenarios to minus $13 trillion under dry scenarios (Strzepek et al. 2013).

10.3.10. Summary

Economic impacts of climate change on water related economic sectors have been dominated by incurred economic losses, including flooding, scarcity and cross sectoral induced impacts. Flooding and drought can have major economic costs, in term of impacts (capital destruction, disruption) whereas estimates of adaptation costs (construction, defensive investment) remain relatively modest. Water scarcity and competition for water, driven by institutional, economic or social factors, may mean that water assumed to be available for a sector is not.

10.4. Transport

The impact of climate change on transport has received qualitative, but limited quantitative, focus in the published literature. The impact depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones:

Geographic Zone	Vulnerabilities to Changes in Climate
Freezing/Frost Zone	Permafrost, freeze-thaw cycles, precipitation intensity
Temperate Zone	Change in Precipitation intensity, maximum daily precipitation
Tropical Zone	Change in Precipitation intensity, maximum daily precipitation

As detailed below, several studies have actively explored the potential impacts of climate change on the transport sector, focusing on overall impacts such as impacts on transportation safety or disruptions of transportation service. Quantitative, economic analyses of the impact on physical infrastructure include (Larsen *et al.*, 2008; Chinowsky *et al.*, 2010; Hunt and Watkiss, 2010; Chinowsky *et al.*, 2011) and on wider economic implications (Arndt, 2012).

10.4.1. Roads

Studies on the direct effects of climate change on road networks are primarily focused on qualitative predictions and surveys concerning road impacts on road durability (TRB, 2008b; Koetse and Rietveld, 2009) (Eisenack et al 2012 ; Ryley and Chapman 2012) with some studies of the quantitative effects (MacArthur et al 2012; Nemry and Nemirel 2012). Chapter 8 addresses the indirect effects of climate change on roads in the areas of congestion and safety.

Paved road degradation is directly related to weather stressors that can lead to softening of the pavement as temperatures exceed design thresholds (Lavin, 2003) and an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA, 2006). The melting of permafrost in northern climates as well as increased precipitation and flooding threaten the integrity of road base and sub-bases. Drainage presents a specific problem for urban areas that experience rainfall above their built capacity and will impact design standards and costs for urban transport (CCTF, 2008; Hunt and Watkiss, 2010; Lemmen and Warren, 2010). Increased fire danger from droughts could also pose a threat to roads.

Unpaved roads are vulnerable to a number of climate-based factors especially to increasingly intense precipitation, leading to wash out and disruption of service. In cold climates, temporary winter roads are susceptible to warming and associated lower connectivity of rural areas and reduced economic activity in Northern climates (Mills and Andrey, 2002). Warming could imply that ice roads can no longer be maintained.

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, sea level rise, extreme events and incidence of freeze-thaw cycles (Nemry and Nemirel 2012). In Northern climates, the melting of permafrost (URS, 2010) may lead to ground settlement, undermining stability (Larsen *et al.*, 2008). Increased temperatures pose a threat to rail through thermal expansion. In urban areas, increased temperatures pose a threat to underground transport systems that will see a burden on increased need for cooling systems (Hunt and Watkiss, 2010). For example, £178 million has been allocated to finding a workable solution for increasing the capacity of London's underground cooling system (Arkell and Darch, 2006).

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines, compromised stability of bases built on permafrost, and increases in necessary maintenance (TRB, 2008a;

URS, 2010). Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points. There has been no economic assessment of the impacts.

10.4.4. Shipping

Impacts of inland navigation vary widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to be negative, and are region-specific.

Increased frequency of flood periods will stop ship traffic on the Rhine more often. Longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates due to limited load carrying capacity of the river. Current projects on channel improvements can only partly alleviate these problems (Middelkoop *et al.*, 2001a). Economic impact could be substantial given the value of navigation on the Rhine (Krekt et al., 2011). See Chapter 23 for more detail.

(Millerd, 2010) analyzes the economic impacts of lower water levels in the Great Lakes, with consequent reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of the atmospheric carbon dioxide could increase annual transportation costs by 29%. More moderate climate change could result in a 13 percent increase in annual shipping costs. The impacts vary between commodities and routes.

Warming is *very likely* to lead to increased ice-free navigation and longer shipping season, but *is very likely* also lead to lower water levels from reduced runoff (Lemmen and Warren, 2010). In cold regions, increased days of ice-free navigation and a longer shipping season could positively impact shipping and reduce transportation costs (TRB, 2008b; Koetse and Rietveld, 2009; UNCTAD, 2009; UNECE and UNCTAD, 2010).

Ports will be affected by higher temperatures, sea level rise, increasingly severe storms, and increased precipitation (Becker *et al.*, 2011) (Nursey-Bray and Miller 2012; Nicholls, R. J. et al.,2008). Over $3 trillion in assets in 136 of the world's largest port cities are vulnerable to weather events (Potter *et al.*, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010).

Increased storminess in certain routes may raise cost of shipping through additional safety measures or longer routes that are less storm prone (UNCTAD, 2009; UNECE and UNCTAD, 2010). Transport costs would increase or new routes sought if storms disrupt supply chains by destroying port infrastructure connecting road or rail (Becker *et al.*, 2011). Increased storminess may also affect passage through lock systems (Potter *et al.*, 2008; UNCTAD, 2009). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays.

10.4.5. Air

Hotter air is less dense. In summer months, especially at airports located at high altitudes, this will result in limitations for freight capacity, safety, and weather-related delays, unless runways are lengthened (TRB, 2008a; Pejovic *et al.*, 2009). (Chapman, 2007) suggests that technological innovations will negate the challenges posed by extreme temperatures Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Pejovic *et al.*, 2009; Lemmen and Warren, 2010), with associated economic losses.

The impact of climate change on airport pavement is very similar to paved roads (DOT, 2002; Fortier *et al.*,). The effect of temperature on airports thus imposes a risk to the entire facility (Pejovic *et al.*, 2009) and related economic activity.

10.5. Other Primary and Secondary Economic Activities

This section assesses the impact of climate change on primary (agriculture, mining) and secondary economic activities (manufacturing, construction), unless they are discussed elsewhere in the chapter or the report.

10.5.1. Primary Economic Activities

Primary economic activities (e.g. agriculture, forestry, fishing, mining) are particularly sensitive to the consequences of climate change because of their immediate dependence on the natural environment. In some regions, these activities dominate the economy.

10.5.1.1. Crop and Animal Production

Chapter 7 assesses the impact of climate change on agriculture, including the effects on (international) markets for crops.

10.5.1.2. Forestry and Logging

Chapter 4 assesses the biophysical impact of climate change on forestry. Including adaptation in forest management, climate change would accelerate tree growth. This would reduce prices to the benefits of consumers all around the world. Low to mid latitude producers would benefit too as they switch to short-rotation plantations. Mid to high latitude producers would be hurt by lower prices while their productivity increases only modestly (Sohngen and Mendelsohn, 1997; Sohngen and Mendelsohn, 1998; Sohngen *et al.*, 2001); (Perez-Garcia *et al.*, 2002; Lee and Lyon, 2004; *Adaptation of Forests and People to Climate Change -- A Global Assessment Report.*2009). However, increased biomass prices may impact different forest based industries in different ways given their demand for renewable energy from the biomass sources (Moiseyev *et al.*, 2011).

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses the impact of climate change on freshwater ecosystems, and Chapter 5, 6 and 30 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets. Adaptation and markets would substantially change the effect of climate change on fisheries (Link and Tol, 2009; Yazdi and Fashandi, 2010).

(Allison *et al.*, 2009), using an indicator based approach, analyzed the vulnerability of capture fishery of 132 economies. They find, incongruously, that the sign and size of climate-driven change for particular fish stocks and fisheries are uncertain but are *likely* to lead to either increased economic hardship or missed opportunities for development in countries that depend upon fisheries but lack the capacity to adapt. A major part of the gross turnover of nine key fish and cephalopod species in the Bay of Biscay remains potentially unaffected by climate change (Floc'h *et al.*, 2008). In contrast, Iberian-Atlantic sardine biomass and profitability declines due to climate change (Garza-Gil *et al.*, 2011). The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; McGoodwin, 2007; Eide, 2008; McIlgorm, 2010; Merino *et al.*, 2010).

Ocean acidification has a range of impacts on the biological systems (Doney *et al.*, 2009), but the studies on the economic impacts of ocean acidification are rare. (Brander *et al.*, 2012) estimate the economic impacts of ocean acidification on coral reefs under four IPCC marker scenarios using value transfer function approach and find that the annual economic impacts increase rapidly overtime, though it remains a small fraction of total income. Using a partial equilibrium model, (Narita *et al.*, 2012) estimate the economic impact of ocean acidification on shellfish, mollusks. By the turn of this century the cost of could be over $100 billion.

10.5.1.4. Mining and Quarrying

Climate change would affect exploration, extraction, production, and shipping in the mining and quarrying industry (Pearce *et al.*, 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs. Most infrastructure was built based on presumption of a stable climate, and is thus not adapted to climate change (Ford *et al.*, 2010; Ford *et al.*, 2011; Pearce *et al.*, 2011).

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change would impact manufacturing through three channels. First, climate change affects primary economic activities (see above), and this means that prices and qualities of inputs are different. Second, the production process is affected, or the quality of the product. The impact of climate change on energy demand is well understood (see 10.2). Using a biophysical model of the human body, (Kjellstrom *et al.*, 2009a) project labour productivity to fall, particularly of manual labour in humid climates. (Hübler *et al.*, 2008) uphold the finding with a German case study, and (Hsiang, 2010) corroborate it with a statistical analysis of weather data and labour productivity in the Caribbean for 1970-2006. Some manufacturing activity is location specific, perhaps because it is tied to an input or product market, and will thus have to cope with the current and future climate; other manufacturing has discretion over its location (and hence its climate). Third, climate change affects the demand for products. This is pronounced in manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see below). Unfortunately, there are only a few studies that quantify these effects (see Appendix A).

10.5.2.2. Construction and Housing

Climate and climate change affect construction in three ways. First, weather conditions are one of the key factors in construction delays and thus costs. Climate change would change the length of the building season. Additionally, precipitation affects the cost of construction through temporary flood protection (coffer) structures, slope stabilization management and dewatering of foundations. There are adaptation measures that may reduce some of the costs. (Apipattanavis *et al.*, 2010) show a reduction in the expected value of road construction delays and associated costs. Second, buildings and building materials are designed and selected to withstand a particular range of weather conditions. As climate changes, design standards will change too. Exterior building components including windows, roofing, and siding are all specified according to narrow environmental constraints. Climate change would introduce conditions that are outside the prescribed operating environment for many materials, resulting in increased failures of window seals, increased leaks in roofing materials, and reduced lifespan of timber or glass-based cladding materials. Similarly, the interior building systems that allow for proper airflow in a facility face significant issues with climate change. For example, the increases in temperature and precipitation will lead to increased humidity as well as indoor temperatures. This requires increased airflow in facilities such as hospitals, schools, and office buildings, that is, upgrades to air conditioning and fan units and perhaps further renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters would imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. In 2011, it accounted for 9% of global expenditure, and employed 260 million people (WTTC, 2011). Supply of tourism services is the dominant activity in many regional economies.

Recreation and tourism encompass many activities, some of which are more sensitive to weather and climate than others: compare sunbathing to angling, gambling, business seminars, family visits, and pilgrimage. Climate change would affect the place, time and nature of these activities.

There is a large literature on the impact of climate change on tourism (Gössling *et al.*, 2012; Scott *et al.*, 2012a; Pang *et al.*, 2013). Some studies focus on the changes in the behavior of tourists, that is, the demand for recreation and tourism services (see 10.6.1). Other studies look at the implications for tourist operators and destinations, that is, the supply of recreation and tourism services (see 10.6.2). A few studies consider the interactions between changes in supply and demand (see 10.6.3).

10.6.1. Recreation and Tourism Demand

Conventionally, recreation does not involve an overnight stay whereas tourism does. That implies that recreation, unlike tourism, is done close to home (while leisure is done at home). Whereas tourists, to a degree, chose the climate of their holidays, recreationists do not (although climate is a consideration in the choice where to live). Tourists would adapt to climate change by changing the location, timing and activities of their holidays; recreationists would adapt only timing and activities (Smith, 1990).

10.6.1.1. Recreation

There has been no research on systematic differences of recreational behaviour due to differences in climate at large spatial scales. The impact of climate change on recreation is therefore largely unknown. The economic impact is probably limited, as people are more *likely* to change the composition rather than the level of their time and money spent on recreation. For instance, (Shaw and Loomis, 2008) argue that climate change would increase boating, golfing and beach recreation at the expense of skiing.

There are case studies of the impact of climate change on recreation. (Buckley and Foushee, 2012) find that a trend toward earlier visits to US national parks between 1979 and 2008. They argue this is due to climate change, but do not rigorously test this hypothesis nor control for other explanations. (Dempson *et al.*, 2001) note that the salmon fishery in Newfoundland is closed during hot weather and low water levels. (Ahn *et al.*, 2000) study the impact of climate change on recreational trout fishing in the Southern Appalachian Mountains, and (Whitehead *et al.*, 2009) the effect of sea level rise on sea shore fishing in North Carolina, finding a substantial decrease in the recreational value of these activities. (Daugherty *et al.*, 2011) conclude that climate change will make it more difficult to guarantee adequate water levels for boating and angling in artificial reservoirs. (Pouta *et al.*, 2009) project a reduction in cross-country skiing in Finland, particularly among women, the lower classes, and urban dwellers. (Shih *et al.*, 2009) find that weather affects the demand for ski lift trips. One could expect people to adopt other ways of enjoying themselves but such alternatives were excluded from these studies. There are positive effects too. (Richardson and Loomis, 2005) find that climate change would make trips to the Rocky Mountain National Park more enjoyable. (Scott and Jones, 2006; Scott and Jones, 2007) foresee an increase in golf in Canada due to climate change, (Kulshreshtha, 2011) sees positive impacts on Canadian recreation in general, and (Coombes *et al.*, 2009) predict an increase in beach tourism in East Anglia. (Graff Zivin and Neidell, 2010) find that people recreate indoors when the weather is inclement. (Scott *et al.*, 2007) estimate the relationship between visitors to Waterton Lakes National Park and *weather* variables for eight years of monthly observations; and use this to project an increase in visitor numbers due to *climate change*. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; WTO and UNEP, 2008) and weather (Rosselló-Nadal *et al.*, 2010; Álvarez-Díaz and Rosselló-Nadal, 2010; Rossello, 2011; Førland *et al.*, 2012; Day *et al.*, 2013; Falk, 2013) are important factors in tourist destination choice, and the tourist sector is susceptible to extreme weather (Forster *et al.*, 2012; Forster *et*

al., 2012; Hamzah *et al.*, 2012; Tsai *et al.*, 2012). (Eijgelaar *et al.*, 2010), for instance, argues that so-called "last chance tourism" is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. (Farbotko, 2010; Prideaux and Mcnamara, 2012) use a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice, but (Huebner, 2012) find no impact of future climate change on current travel choices. (Taylor and Ortiz, 2009) show that domestic tourists in the UK often respond to past weather. The hot summer of 2003 had a positive impact on revenues of the tourist sector. (Denstadli *et al.*,) find that tourists in the Arctic do not object to the weather in the Arctic. (Gössling *et al.*, 2006) reaches the same conclusion for tourists on Zanzibar, and (Moreno, 2010) for tourists in the Mediterranean.

(Maddison, 2001) estimates a statistical model of the holiday destinations of British tourists, (Lise and Tol, 2002) for Dutch tourists and (Bigano *et al.*, 2006) for international tourists from 45 countries; these models control for as other variables as possible. Tourists have a clear preference for the climate that is currently found in Southern France, Northern Italy and Northern Spain. People from hot climates care more about the climate in which they spend their holidays than people from cool climates. (Bujosa and Rosselló, 2012) study destination choice within Spain, and find the climate change would induce a northward shift.

However, whereas (Bigano *et al.*, 2006) find regularity in revealed preferences, (Scott *et al.*, 2008b) find pronounced differences in stated preferences between types of people. The impact of climate change on tourism demand may be more complicated than suggest by the econometric analyses reviewed above (Gössling and Hall, 2006).

(Hamilton *et al.*, 2005a; Hamilton *et al.*, 2005b; Bigano *et al.*, 2007) use the above econometric analyses to construct a simulation model of domestic and international tourism. (Hamilton and Tol, 2007) downscale the national results of these studies to the regions of selected countries. The advantage of such a model is that it considers the simultaneous change in the attractiveness of all potential holiday destinations (Dawson and Scott, 2013). The disadvantage is its stylized representation of the effect of climate on destination choice. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in hotter countries, and rise in colder countries. Tourists from Northwestern Europe, the main origin worldwide of international travelers at present, would be more inclined to spend the holiday in their home country, so that the total number of international tourists falls. Second, the impact of climate change is dominated by the impact of population growth and, particularly, economic growth. In the worst affected countries, climate change slows down, but nowhere reverses, growth in the tourism sector.

10.6.2. Recreation and Tourism Supply

There are a number of biometeorological studies of the impact of climate change on tourism. (Yu *et al.*, 2009a) find that Alaska has become more attractive over the last 50 years, and Florida less attractive to tourists. (Yu *et al.*, 2009b) conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. (Scott *et al.*, 2004) show that climate change would make Mexico less attractive to tourists, and Canada more attractive. Florida and Arizona would lose market share in US tourism. (Perry, 2006) speculates that the hot summer of 2003 had a negative impact on tourism in the Mediterranean. (Matzarakis *et al.*, 2010) construct a composite index of temperature, humidity, wind speed and cloud cover, and use this to map tourism potential. (Lin and Matzarakis, 2008; Lin and Matzarakis, 2011) apply the index to Taiwan and Eastern China. (Endler and Matzarakis, 2010a; Endler and Matzarakis, 2010b; Endler and Matzarakis, 2011) use an index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes; the latter aspect is thoroughly investigated by (Endler *et al.*, 2010). (Zaninović and Matzarakis, 2009; Matzarakis and Endler, 2010) use this method to study Freiburg and Hvar. (Matzarakis *et al.*, 2007) project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. (Amelung and Viner, 2006; Hein *et al.*, 2009; Perch-Nielsen *et al.*, 2009; Giannakopoulos *et al.*, 2011; Amelung and Moreno, 2012; Amengual *et al.*, 2012) reach the same conclusion, but also point out that Mediterranean tourism may shift from summer to the other seasons. (Giannakopoulos *et al.*, 2011) notes that coastal areas in Greece may be affected more than inland areas because, although temperature would be lower, humidity would be higher. (Moreno and Amelung, 2009), on the other hand, conclude that climate change will not have a major impact (before 2050) on

beach tourism in the Mediterranean because sunbathers like it hot (Moreno, 2010; Rutty and Scott, 2010). (Amelung *et al.*, 2007) use a weather index for a global study of the impact of climate change on tourism, finding shifts from equator to pole, summer to spring and autumn, and low to high altitudes. (Perch-Nielsen, 2010) combines a meteorological indicator of exposure with indicators of sensitivity and adaptive capacity. She uses this to rank the vulnerability of beach tourism in 51 countries. India stands out as the most vulnerable, and Cyprus as the least vulnerable.

The main criticism of most biometeorological studies is that the predicted gradients and changes in tourism attractiveness have rarely been tested to observations of tourist behaviour. (De Freitas *et al.*, 2008) validate their proposed meteorological index to survey data. (Moreno *et al.*, 2008) and (Ibarra, 2011) use video of beach occupancy to test meteorological indices for beach tourism. (Gómez-Martín, 2006) tests meteorological indices against visitor numbers and occupancy rates. All four studies find that weather and climate affects tourists, but in a different matter than typically assumed by biometeorologists.

Studies on the supply side often focus on ski tourism. (Abegg and Elsasser, 1996) is one of the earliest papers. Warming of would raise the altitude of snow-reliable resorts, and fewer resorts would be snow-reliable (Hendrikx *et al.*, 2012; Steger *et al.*, 2012). (Elsasser and Bürki, 2002) argue that artificial snow-making cannot fully offset the loss in natural snowfall in the Swiss Alps. (Schmidt *et al.*, 2012) show that snow-making is less successful in lower areas, although that is the current strategy of operators in Austria (Wolfsegger *et al.*, 2008; Morrison and Pickering, 2012). (Hamilton *et al.*, 2007) highlight the importance of "backyard snow" to induce potential skiers to visit ski slopes. (Pickering *et al.*, 2010) find that skiers in Australia prefer natural snow over artificial snow. From a series of interviews, (Hill *et al.*, 2010) find that tourist operators in the Swiss Alps seek to maintain the status quo through adaptation, rather than search for viable alternatives to ski tourism; and argue that better coordination is needed for adaptation to be successful. (Scott and McBoyle, 2007) highlight that there are many options to adapt to a loss of snow for skiing. (Hoffmann *et al.*, 2009) use a survey of ski lift operators in the Swiss Alps. They find that the need for adaptation exceeds the ability to adapt and that adaptation is more prevalent on higher slopes (which are less vulnerable). (Scott *et al.*, 2006) study the impact of climate change on ski areas in eastern North America. Even with snowmaking, climate change could be an existential threat to 3 of the 6 ski areas by 2050; and climate change would lead to a contraction in each area in each scenario. (Dawson *et al.*, 2009) use past analogues to study the impact of future climate change on ski tourism in the Northeastern USA. They find that small and very large resorts will be hit hardest, and low-lying ones. (Scott *et al.*, 2008a) find that snowmobiling would have disappeared from the Northeastern USA by the end of the 21st century. (Mcboyle *et al.*, 2007) find the same for the Canadian lowlands. (Matzarakis *et al.*, 2012)Artificial snowmaking would halt the decline of ski resorts, but water scarcity and the costs of snowmaking would be increasingly large problems. (Scott *et al.*, 2003) reach the same conclusion for southern Ontario, (Scott *et al.*, 2007) for Quebec, (Hendrikx and Hreinsson, 2012) for New Zealand, (Steiger and Mayer, 2008) for Tyrol, and (Pons-Pons *et al.*, 2012) for Andorra. (Bicknell and Mcmanus, 2006) study adaptation for ski resorts in Southeastern Australia. They note that resorts may continue to be economically viable in the absence of snow by focusing on alternative activities. (Pickering and Buckley, 2010) note that artificial snow-making may be infeasible and uneconomic at the scale required to offset the loss of natural snow in Australia, and argue for a reorientation towards summer tourism and residential property development. (Moen and Fredman, 2007) find that alpine ski resorts in Sweden would become economically unviable, and that alternative livelihoods need to be developed. (Tervo, 2008) finds that the shortening of the Finnish ski season would be too limited to affect the economic viability of tourist operators, but (Landauer *et al.*, 2012) find that Finnish ski operators would find it difficult to convince their clients of the need to adapt. (Serquet and Rebetez, 2011) find that the Swiss Alps attract more tourists during hot summers, and argue that climate change would structurally improve the mountains as a summer tourism destination. (Matzarakis *et al.*, 2012) also argue that a proper assessment considers all seasons, using Austria as an example. (Bourdeau, 2009) argue along the same lines for the French Alps, stressing the importance of non-tourism alternatives as a source of economic development. (Steiger, 2010) finds that stakeholders in Tyrol think that gains in summer would not fully offset losses in winter. (Potocka and Zajadacz, 2009) argue that prudent management supplies tourism services suitable for all weather. (Steiger, 2012) finds that, in the first half of this century, demographic trends are more important to skiing in Austria than climate change. (Hopkins *et al.*, 2012) also argue that other factors dominate the impact of climate change.

Other studies consider beach tourism. (Scott *et al.*, 2012b) highlight the vulnerability of coastal tourism facilities to sea level rise. (Hamilton, 2007) finds that tourists are averse to artificial coastlines, so that hard protection measures against sea level rise would reduce the attractiveness of an area. (Raymond and Brown, 2011) survey tourists on the Southern Fleurieu Peninsula. They conclude that tourists who are there for relaxation worry about climate change, particularly sea level rise, while tourists who are there to enjoy nature (inland) do not share that concern. (Becken, 2005) finds that tourist operators have adapted to weather events, and argues that this helps them to adapt to climate change. (Belle and Bramwell, 2005) find that tourist operators on Barbados are averse to public adaptation policies. (Uyarra *et al.*, 2005) find that tourists on Barbados would consider holidaying elsewhere if there is severe beach erosion. (Buzinde *et al.*, 2010a; Buzinde *et al.*, 2010b) find that there is a discrepancy between the marketing of destinations as pristine and the observations of tourists, at least for Mexican beach resorts subject to erosion. They conclude that tourists have a mixed response to environmental change, contrary to the officials' view that tourists respond negatively. (Jopp *et al.*, 2013) find that an increase in tourism in the shoulder season may offset losses in the peak season in Victoria.

Some studies focus on nature tourism. (Wall, 1998) notes the impact of climate change on water-based tourism, on the coast through sea level rise and inland through drought. (Cavan *et al.*, 2006) find that climate change may have a negative effect on the visitor economy of the Scottish uplands as natural beauty deteriorates through increased wild fires. (Saarinen and Tervo, 2006) interviewed nature-based tourism operators in Finland, and found that about half of them do not believe that climate change is real, and that few have considered adaptation options. (Nyaupane and Chhetri, 2009) argue that climate change would increase weather hazards in the Himalayas and that this would endanger tourists. (Uyarra *et al.*, 2005) find that tourists on Bonaire would not return if coral was bleached. (Hall, 2006) finds that small tourist operators in New Zealand do not give high priority to climate change, unless they were personally affected by extreme weather in recent times. The interviewed operators generally think that adaptation is a sufficient response to climate change for the tourism sector. (Klint *et al.*, 2012) find that tourist operators in Vanuatu give low priority to adaptation to climate change and (Jiang *et al.*, 2012) find Fiji poorly prepared. (Saarinen *et al.*, 2012) find that tourist operators in Botswana think that climate change would not affect them. (Wang *et al.*, 2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China.

While the case studies reviewed above provide rich detail, it is hard to draw overarching conclusions. A few studies consider all aspects of the impact of climate change for particular countries or regions. (Ren Guoyu, 1996) shows that domestic tourism in China would shift northwards, that sea level rise would damage some tourist facilities, and that the overall impact of climate change on China's tourist sector would be negative. (Harrison *et al.*, 1999) conclude that climate change would make Scotland less attractive to tourists in winter but more attractive in summer. (Ceron and Dubois, 2005) assess the impact of climate change on tourism in France. They argue that the French Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain. The Atlantic Coast, although warming, would not become more attractive because of increased rainfall. It is not probable that the increase in summer tourism in the mountains would offset the decrease in winter tourism. (Jones *et al.*, 2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and fret that the dates of the Tulip Festival may need to be shifted to reflect changing phenology. (Dawson and Scott, 2010) assess the impacts in the Great Lakes regions, finding reduced tourism potential in winter but increased opportunities in summer. (Turton *et al.*, 2010) conclude that tourist operators in Australia find the uncertainty about climate change too large for early investment in adaptation.

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of rather stylized climate-change-induced changes in tourism supply and demand. Both studies use a computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. (Berrittella *et al.*, 2006a) consider the consumption pattern of tourists and their destination choice. They find that the economic impact is qualitatively the same as the impact on tourist flows (discussed above): Colder countries benefit from an expanded tourism sector, and warmer countries lose. They also find a drop in global welfare, because of the redistribution of tourism supply from warmer (and poorer) to colder

(and richer) countries. (Bigano *et al.*, 2008a) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists typically are sufficiently valuable to be protected against sea level rise. The study finds that the economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; and that the welfare losses due to the impact of climate change on tourism are larger than the welfare losses due to sea level rise.

10.7. Insurance

10.7.1. Main Results of AR4 and SREX

More intense or frequent weather-related disaster would affect property insurance, which is growing with the economy everywhere (WG II, 7.4.2.2.4). Insurability can be preserved through risk-reducing measures. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. Improved risk management would further financial resilience (WG II, 7.4.2.2.4., 7.6.3). Insurance is linked to disaster risk reduction and climate change adaptation, because it enables recovery, reduces vulnerability and provides knowledge and incentives for reducing risk ((IPCC, 2012)).

10.7.2. Societal Role of Insurance Covering Weather Hazards

Insurance internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals and enterprises, thus stabilizing income and consumption, and decreasing societal vulnerability. Insurance is based on the law of large numbers: the larger the pool of uncorrelated and relatively small risks, the more accurately the average loss per policy can be predicted and charged accordingly, allowing for a lower premium than with a smaller pool. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods simultaneously affect many, and thus violate the principle of uncorrelated risks. Consequently, large losses are much more *likely*, the loss variance is greater, and the tail risk is higher ((Kousky and Cooke, 2012)). If insurance coverage is to be maintained, insurers would need more risk capital to indemnify catastrophic losses and remain financially solvent. This coverage is purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather insurance are subjects of ongoing research given future climate change ((Charpentier, 2008); (Maynard and Ranger, 2012); (Clarke and Grenham, 2012)).

Increasing volatility and burden of losses in many regions are expected to fundamentally impact on the industry, leading insurers to adapt their business to the changing risk ((Herweijer *et al.*, 2009); (Phelan *et al.*, 2011); (Mills, 2012); (Paudel, 2012)).

10.7.3. Observed and Projected Insured Losses from Weather Hazards

Direct and insured losses from weather-related disasters have increased substantially in recent decades both globally and regionally ((IPCC, 2012); (Bouwer *et al.*, 2007); (Swiss Re, 2012); (Munich Re., 2012); (Crompton and McAneney, 2008); (Gall *et al.*, 2011); (Smith and Katz, 2013)). Substantially fluctuating global insured weather-related losses in the period 1980-2008 increased by US^{2008}1.4bn per year on average (Barthel and Neumayer, 2012). As a rule, insured loss figures are more accurate than direct economic loss estimates, because insurance procedures and payouts are regulated and monitored. Hence, estimates of direct overall losses are often derived from insurance losses ((Kron *et al.*, 2012); (Smith and Katz, 2013)). Economic growth, including greater concentrations of people and wealth in periled areas and rising insurance penetration, is the most important driver of the increase in losses.

Growth induced changes in past losses are removed by normalizing to current levels of destructible wealth. So far, there is only one study analyzing global normalized weather-related insured losses, but the period (1990-2008) is too short to infer any reliable trend (Barthel and Neumayer, 2012). A few studies focus on specific perils and regions, in

particular Australia, USA and Europe. Trends were detected for the USA and Germany, but not for Australia and Spain (Table 10-4). Trends in normalized insured losses can be influenced not only by changing hazards but also by changing damage sensitivities, adaptive measures, different normalization, and changes in insurance ((Barthel and Neumayer, 2012); (Crompton and McAneney, 2008); (Bouwer, 2011); (IPCC, 2012)). Prevention measures such as flood control structures, or improved building standards over time, would offset an increase in hazard ((Kunreuther *et al.*, 2009)). The 2011 Mississippi flood resulted in US$4.6bn direct losses, but losses exceeding US$200bn were avoided by flood controls, according to the U.S. Army Corps of Engineers ((Kron and Steuer, 2012); DeHaan *et al.*, 2012). Given such confounding factors, it is challenging to estimate to what degree developments in losses convey a climate signal ((Kron, 2012); (IPCC, 2012)). Studies analyzing changes in climate variables and losses in parallel are still rare. The number of days that a regional insurer in southwest Germany sustains hail losses displays an upward trend since 1986, while meteorological severe storm indicators also show upward trends ((Kunz *et al.*, 2009)). Variability and mean level of thunderstorm-related insured losses in the USA in the period 1970-2009 have substantially increased, while meteorological thunderstorm forcing potential has risen in parallel ((Sander *et al.*, 2013)). (Corti *et al.*, 2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961-2002, consistent with an increase in dryness in central and southern Europe ((IPCC, 2012)). The observed rise in US normalized insured flood losses (Barthel and Neumayer, 2012) may partly correspond to *likely* increased heavy precipitation events in parts of the USA ((IPCC, 2012) , AR5WG1-2.6.2.1), while the evidence for climate driven changes in river floods is non-compelling ((IPCC, 2012)). The recent upswing in hurricane hazard and losses appears to be connected to multi-decadal climate variability ((Lonfat *et al.*, 2007); AR5WG1-Box14.2; AR5WG1-14.7.3). Loss trends have not been conclusively attributed to anthropogenic climate change, and sientific attribution methods have not been applied.

[INSERT TABLE 10-4 HERE
Table 10-4: Observed normalized insured losses from weather hazards.]

Many (AO)GCM-based projections agree that extreme winter storm wind speeds fall in the Mediterranean and increase in west, central, and northern Europe. Loss ratios, i.e. insured loss divided by insured value, follow the same pattern (e.g., (Schwierz *et al.*, 2010); (Donat *et al.*, 2011); (Pinto *et al.*, 2012); AR5WG1-Box14.3) (Table 10-5). Return periods per loss level are projected to shorten in large parts of Europe, indicating more frequent high losses (e.g., (Pinto *et al.*, 2012)) (Table 10-5). Projected overall losses and fatalities develop accordingly ((IPCC, 2012); (Narita *et al.*, 2010)). Across three modeling approaches calibrated to German insurance data, the 25-year loss is projected to change by –10% to +18% (2011-2040), +5% to +41% (2041-2070), and +45% to +58% (2071-2100) against 1971-2000, keeping exposures and damage sensitivities constant (A1B, (Held *et al.*, planned 2013)).

[INSERT TABLE 10-5 HERE
Table 10-5: Climate change projections of insured losses and/or insurance prices.]

Direct losses and fatalities from flooding will increase with climate change in many locations in the absence of adequate adaptation ((IPCC, 2012); AR5WG1-12.4.5.5; 11.3.2.5.2). Mean annual insured heavy rainfall and flood losses in the UK, the Netherlands, southern Norway and the Canadian province of Ontario were projected to rise with climate change; for Germany an increase of more than 90% in insured river inundation losses in the period 2041-2070 relative to the late 20th century was projected, keeping exposures and sensitivities constant ((Hattermann *et al.*, planned 2013)) (Table 10-5).

Direct losses and fatalities from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins ((IPCC, 2012); AR5WG1-Box14.3; (Peduzzi *et al.*, 2012)). Studies for the North Atlantic project a climate-driven loss increase ((Pielke, 2007); (Emanuel, 2011)). (Ranger and Niehoerster, 2012), (Kunreuther *et al.*, 2012), and (Raible *et al.*, 2012) found insured losses change in opposite directions across a range of dynamical and statistical model projections. Insured typhoon-related property losses in China are projected to increase ((Dailey *et al.*, 2009)). Averaged across four GCMs, (Mendelsohn *et al.*, 2012) project rising climate driven direct losses for the coasts of Central America, the Caribbean, North America, and East Asia. (Narita *et al.*, 2009) report an increase in damages and fatalities in all parts of the world.

Hailstorm insurance losses in the Netherlands ((Botzen *et al.*, 2010b)) and Germany ((Gerstengarbe *et al.*, 2013)) are projected to increase. Paddy rice insurance payouts are projected to decrease ((Iizumi *et al.*, 2008)) (Table 10-5).

Rising insured wealth will increase both losses and premium income, not necessarily altering the ratio of both, indicating impact. Such automatic compensation is not effective for external drivers of loss, such as changing hazard properties. Hence, projection studies using ratios of losses to premiums or sums insured (while assuming constant insured property) can be justified as an approximation of the climate change impact (e.g., (Donat *et al.*, 2011)). Consequently, future economic growth is rarely projected ((Aerts and Botzen, 2011)).

10.7.4. Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

The provision of weather hazard insurance is contingent on an insurer's ability to find a balance between affordability of the premiums and costs that have to be covered by the revenue. On the cost side, the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing are included. Moreover, the revenue must provide a return on shareholders' equity and allow for the purchase of external capital if large losses are incurred ((Charpentier, 2008); (Kunreuther *et al.*, 2009)).

The balance between affordability and profitability is sensitive to climate change. Increases in large weather-related losses may corrode an insurer's solvency if it fails to reflect the changes in its risk management, or is hampered in doing so by price regulation, as was the case with the upswing in Atlantic hurricane activity in the USA since the mid-1990s ((Grace and Klein, 2009)). Additionally, misguided incentives for development in hazard-prone areas, as with the US National Flood Insurance Program ((Kousky and Kunreuther, 2010); (Michel-Kerjan, 2010); (GAO, 2011)), can aggravate the situation (Table 10-6).

[INSERT TABLE 10-6 HERE
Table 10-6: Supply-side challenges and sensitivities.]

The additional uncertainty induced by climate change translates into a need for more risk capital ((Charpentier, 2008); (Kunreuther *et al.*, 2009); (Grace and Klein, 2009)). This raises insurance premiums and affects the economy (Table 10-6). Health and life insurance are also affected through the health impacts of climate change ((Hecht, 2008); (Leurig, 2011)). Liability insurance, too, may be susceptible to climate change. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending ((Mills, 2009); (Heintz *et al.*, 2009); (Patton, 2011)). A decision by the Supreme Court of Virginia in April 2012 denied defense costs under the specific liability insurance policy of an utility company (Supreme Court of Virginia, U.S.A., 2012)) (Table 10-6).

10.7.4.2. Middle- and Low-Income Countries

Middle- and low-income countries account for a small share of worldwide non-life insurance: 16% of premiums in 2011 ((Swiss Re, 2013b)). In high-income countries some 40% of direct natural disaster losses have been covered by insurance since 1980, about 4% in middle-income countries and less than 1% in low-income countries ((Wirtz *et al.*, planned 2013); (IPCC, 2012)). For instance, only about 1% of direct overall losses in the 2010 floods in Pakistan were insured ((Munich Re., 2011)).

The small share of insurance in risk financing is not deemed economically prudent, because other options, such as external credit or donor assistance, can be unreliable and late. This leaves a financial gap in the months immediately following the event, often exacerbated by overstretched public finances. Pre-disaster financing instruments such as insurance or trigger-based risk-transfer products are a better means of providing prompt liquidity for households, businesses, and governments ((Ghesquiere and Mahul, 2007); (Linnerooth-Bayer *et al.*, 2009); (IPCC, 2012)). These

may become more important if disaster incidence increases with climate change ((IPCC, 2012); (Collier *et al.*, 2009); (Hochrainer *et al.*, 2010)).

It is challenging to upscale catastrophe insurance because of low business volumes, high transaction costs, and high reinsurance premiums following large disasters. Small-scale insurance schemes in middle- and low-income countries may find it difficult to obtain sufficient risk capital ((Cummins and Mahul, 2009); (Mahul and Stutley, 2010)).

Microinsurance schemes, keeping transaction costs at the lowest operable level, mainly provide health and life cover to households and small enterprises in low-income markets. Supply of property insurance suffers from correlated weather risks, although weather-related agricultural damages are covered. Such weather coverage is growing, typically with government and NGO assistance or cross-subsidies from local insurers ((Linnerooth-Bayer and Mechler, 2011); (Qureshi and Reinhard, 2011)). These schemes may be particularly sensitive to a rise in disaster risk due to climate change ((Collier *et al.*, 2009); (Leblois and Quirion, 2011); (Clarke and Grenham, 2012)).

Adverse selection is another challenge: clients do not always disclose their high risk, e.g. a floodplain site, to the insurer so as to benefit from lower rates. Lower-risk participants are charged too high premiums and leave the scheme, thus increasing overall risk. In low-income countries, where data to establish homogenous risk groups are not available, this can cause disaster insurance markets to fail. Moral hazard is another issue, where the insured adopt more risky behavior than anticipated by the insurer, particularly in the absence of proper monitoring (e.g., (Barnett *et al.*, 2008); (Mahul and Stutley, 2010)).

10.7.5. Products and Systems Responding to Changes in Weather Risks

10.7.5.1. High-Income Countries

A rise in weather-related disaster risk may drive the need for more risk-based capital to cover the losses. There are several options that sustain insurability. Reducing vulnerability often makes sense even if expected climate change impacts will not materialize. Theoretically, risk-based premiums incentivize policyholders to reduce their vulnerability ((IPCC, 2012); (Hecht, 2008); (Kunreuther *et al.*, 2009)) (Table 10-7). Premium discounts for loss-prevention can further promote this ((Ward *et al.*, 2008); (Kunreuther *et al.*, 2009)) (Table 10-7). Moral hazard can be reduced by involving the policyholder to some extent in the payment of losses (deductibles, upper limits of insurance coverage: (Botzen and van den Bergh, 2009); (Botzen *et al.*, 2009)). Collaborative efforts of insurers and governments on damage prevention decrease risk ((Ward *et al.*, 2008); (Reinhold *et al.*, 2012)). For example, new building standards in Florida reduced mean damage per house by 42% in the period 1996-2004 relative to pre-1996 ((Kunreuther *et al.*, 2009)). Risk-based premiums are often hampered by price regulation, subsidies, competitive pressures, bundling of perils in one policy, and availability of data ((Maynard and Ranger, 2012)).

[INSERT TABLE 10-7 HERE
Table 10-7: Products and systems responding to changes in weather risks.]

Most commercial risk-assessment models only incipiently factor in changes in weather hazards, mainly to reflect higher hurricane frequencies ((Seo and Mahul, 2009)), assuming unchanging conditions for other weather hazards. Ignoring changing hazard conditions results in biased estimates of expected loss, loss variability and risk capital requirements ((Lonfat *et al.*, 2007); (Charpentier, 2008); (Watson and Johnson, 2008); (Herweijer *et al.*, 2009); 10.7.3). Other confounding factors, e.g. systemic economic impact, in recent large losses have been addressed (e.g., (Muir-Wood and Grossi, 2008)) (Table 10-7). Geospatial risk-assessment tools, e.g. flood-recurrence zoning with premium differentiation, counteract adverse selection ((Kunreuther *et al.*, 2009); (Mahul and Stutley, 2010)). Some insurers have offered weather alert systems and seasonal agricultural planning systems to clients (e.g., (Niesing, 2004); (*AgroClima. Informática Avanzada SA de CV.*2013)). Credit rating agencies and Solvency II insurance regulation in Europe contribute to enhanced disaster resilience ((Michel-Kerjan and Morlaye, 2008); (Kunreuther *et al.*, 2009); (Grace and Klein, 2009)). Insurers and researchers have projected climate change driven losses to allow

for adaptation of the industry (e.g., (Held *et al.*, planned 2013); (Kunreuther *et al.*, 2012); 10.7.3). Due to its short-term contracts the insurance sector is better adaptable than others ((Botzen *et al.*, 2010a)).

Reinsurers are key to the supply of disaster risk capital. They operate globally to diversify the regional risks of hurricanes and other disasters. Access to reinsurance enhances risk diversification of insurers. Periodic shortages in reinsurance capacity following major disasters have moderated over the last two decades because of easier new capital inflow ((Cummins and Mahul, 2009); (IPCC, 2012)).

Global diversification potential of large losses has fallen over recent decades because of increasing dependence between major insurance markets. For instance, the Thailand floods of 2011 disrupt industrial hubs and global supply chains ((Courbage *et al.*, 2012)).This process may continue with climate change ((Sherement and Lucas, 2009); (Kousky and Cooke, 2012)). However, global diversification potential can be increased by developing insurance markets in middle- and low income countries ((Cummins and Mahul, 2009)).

Very large loss events, say in excess of US$ 100bn, may make additional capacity desirable. These disasters can be diversified in the financial securitization market ((IPCC, 2012)). Natural catastrophe risks are not correlated with capital market risks and hence are attractive to institutional investors. For instance, a catastrophe bond assures the investor above-market returns as long as a parametric index (e.g., wind-based) does not exceed a threshold, but pays the insurer's loss otherwise. The catastrophe bond market reached critical mass after the hurricanes of 2004 and 2005, with some US$ 11bn of risk capital in effect by June 2011 ((Cummins, 2012); (Cummins and Weiss, 2009); (Michel-Kerjan and Morlaye, 2008); (Kunreuther and Michel-Kerjan, 2009)) (Table 10-7).

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance is considered well-suited to the agricultural sector in developing countries (e.g., (Collier *et al.*, 2009); (IPCC, 2012)). Payouts depend on a physical trigger, e.g. cumulative rainfall at a nearby weather station, thus avoiding costly loss assessments. Moral hazard and adverse selection are removed ((Barnett *et al.*, 2008)). Risk-based premiums encourage adaptive responses ((Mahul and Stutley, 2010)) (Table 10-7). Basis risk, where losses occur but no payout is triggered, provokes distrust. Misunderstandings and scaling up of pilots pose further difficulties ((Patt *et al.*, 2010); (Leblois and Quirion, 2011); (Clarke and Grenham, 2012)). Suggested improvements include area-yield indices and coverage at aggregate level to reduce basis risk, and a cooperative architecture ((Clarke and Grenham, 2012); (Biener and Eling, 2012)) (Table 10-7). For both indemnity-based and index-based trigger concepts application prospects are identified, depending on the insured's characteristics and the market setting (Herbold, 2013; Swiss Re, 2013b).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of small states' sovereign risks (CCRIF, Caribbean) ((IPCC, 2012)). In both cases, peak risk is transferred to reinsurance and catastrophe bonds (Table 10-7).

10.7.6. Governance, Public-Private Partnerships, and Insurance Market Regulation

10.7.6.1. High-Income Countries

Theory favors an arrangement where individual risk is insured, but the non-diversifiable component of risk (that may rise with climate change) is public ((Borch, 1962); (Kunreuther *et al.*, 2009)). Accordingly, many high-income states have public-private arrangements involving government intervention on peak risk ((Aakre *et al.*, 2010); (Bruggeman *et al.*, 2010); (Schwarze *et al.*, 2011); (Paudel, 2012)) (Table 10-8). The pro-adaptive, risk-reducing features of insurance are more effective if the price reflects the risk and the pool of insured is larger, e.g. through bundled perils ((Bruggeman *et al.*, 2010); (Paudel, 2012)). People who cannot afford premiums can be covered by vouchers, leaving the price signal undistorted, or by subsidies ((Kunreuther *et al.*, 2009); (Aakre *et al.*, 2010)) (Table 10-8). Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-

term views. Because of climate change, regulators have a new role in risk-adequate pricing, risk education, and risk-reduction in the long term ((Hecht, 2008); (Grace and Klein, 2009); (Mills, 2009); (Leurig, 2011)).

[INSERT TABLE 10-8 HERE
Table 10-8: Governance, public-private partnerships, and insurance market regulation.]

10.7.6.2. Middle- and Low-Income Countries

A key element of risk financing is the transfer of private risks to the insurance market. This reduces the governments' burden and uncertainty due to weather disasters ((Ghesquiere and Mahul, 2007)). Interest in public-private partnerships may evolve, e.g. between government, farmers, rural banks and insurers, in order to expedite agricultural development and resilience, e.g. by means of subsidies for start-up costs and the uppermost risk portion ((Collier *et al.*, 2009); (Mahul and Stutley, 2010)) (Table 10-8). As such systems have suffered from adverse selection and moral hazard ((Coble *et al.*, 1997); (Makki and Somwaru, 2001); (Glauber, 2004)), an improved design is needed. For instance, group policies foster mutual monitoring. Well-designed laws and regulations can encourage purchase of insurance. Insurance pools diversify weather risks across larger regions, reduce premiums and improve access to external risk capital ((Mendoza, 2009); (Hochrainer and Mechler, 2011); (Biener and Eling, 2012); (IPCC, 2012)).

In least developed countries, even incipient domestic insurance markets hardly exist. Climate change-related disaster risk management was proposed for inclusion in the adaptation regime of the UNFCCC. Insurance is a central element in these proposals, financed from an UNFCCC adaptation fund according to the principles of "common but differentiated responsibilities and respective capabilities" (UNFCCC Art.3.1) and "polluter pays" ((AOSIS, 2008); (Swiss Confederation, 2008); (MCII, 2008); (Warner and Spiegel, 2009); (Linnerooth-Bayer *et al.*, 2009); (MCII, 2012); (IPCC, 2012)) (Table 10-8).

Innovative insurance concepts, facilitating greater disaster risk capital, are available in middle- and low-income countries, at least at pilot stage. These can advance adaptation to climate change impacts. Everywhere, risk-based premiums foster risk awareness and risk reduction. Challenges include improved risk assessment, with sufficient detail and appropriate dynamics, and scaling-up of successful pilot schemes. Regulatory requirements for risk capital, and access to reinsurance and securitization market further contribute to a resilient insurance system. These are the provisions of sound risk management, even in the absence of climate change.

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy include waste management, wholesale and retail trade, engineering, government, education, defense and health. Contributions to the economy vary substantially by country; however, overall worldwide economic activity related to government accounts for approximately 30% of global expenditures.

10.8.1 Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is sparse (see Appendix A). Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. (Tamiotti *et al.*,2009) conducted a qualitative assessment of climate and trade. (Travers and Payne, 1998) and (Subak *et al.*, 2000) find that weather significantly affects retail. (Sabbioni *et al.*, 2009) note that climate change may require a greater effort to protect cultural heritage. Chapter 12 discusses the impact of climate change on violent conflict, which has implications for military expenditures.

10.8.2. Health

Climate change-related alterations in weather patterns, particularly extreme weather and climate events, could affect the health sector through impacts on infrastructure and the delivery of health care services from changing demand. Health care facilities are priority infrastructure that can be damaged by storm surges, floods, wildfires, and other weather and climate events, compromising critical resources required for patient treatment; and physical damage and destruction of equipment and buildings (Carthey et al. 2009). Floods and wildfires can require evacuation of critical care patients, with attendant risks for the patients. Adverse impacts on transportation (such as flooded roads) can exacerbate the situation.

Increased demands for services put additional burdens on public health and health care personnel and supplies, with potential economic consequences. For example, more than 600,000 people required immediate assistance in hydrological events in 2002 through 2010 (EM-DAT 2011). Although the proportion seeking medical treatment are typically a small subset, the additional burden on health care facilities can be significant (Hess et al. 2009). Heatwaves and other extreme events can increase hospitalizations (Chapter 11) with attendant increased costs. Individuals looking for an air-conditioned location during high ambient temperatures also can increase hospital visits (Carthey et al. 2009). One trauma center in the U.S. found a 5.25% increase in hourly admissions for each approximately 5°C increase in temperature; and a 60-78% increase in admission for each 2.5 cm increase in precipitation in the previous three hours (Rising et al. 2006). Very large events that affect multiple health care facilities challenge the ability to properly care for the affected and those with ongoing health issues requiring medication or treatment. Areas projected to experience increases in the frequency and intensity of extreme events could consider additional “surge capacity” to increase the ability of health care facilities to manage such events without interruption of service (Banks et al. 2007; Hess et al. 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality: malnutrition, diarrheal diseases, and malaria (Chapter 11). Any increase in health burdens or risks would increase the demands for public health services (e.g. surveillance and control programs) and the demands for health care and relevant supplies (e.g. oral rehydration). Studies estimating the costs of additional cases of climate-sensitive health outcomes focus on the costs of treatment, not the costs of providing additional health services. Other omitted considerations include the costs of all the health risks of climate change, the costs of implementing new policies, and the costs of hedging health impacts under different scenarios (Hutton, 2011).

Health accounts for approximately 10% of global GDP by expenditure. Estimates of the costs of treating additional cases of climate sensitive health outcomes are in the range of billions of US$ annually (Ebi 2008; Pandey 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change, assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO2 equivalent in 2210, and current costs of treatment in developing countries, estimated treatment costs without adaptation could be $4-12 billion worldwide, depending on assumptions of the sensitivity of these health outcomes to climate change (Ebi 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in South East Asia and Africa, to address the projected additional cases of diarrheal disease and malaria (Markandya and Chiabai 2009). The projected additional cases due to climate change were (in millions) 132 for diarrheal diseases; 4.7 for malnutrition; and 22 for malaria. This was against (in millions) 4,514 cases of diarrheal disease, 46 cases of stunting and wasting, and 408 cases of malaria in 2004 (WHO 2004). Development assistance for the health sector in the year 2002 from bilateral and multilateral agencies and foundations was US$ 9.3 billion (Hecht and Shah 2003).

A second global estimate assumed UN population projections, strong economic growth, updated projections of the current health burden of diarrheal diseases and malaria, two climate scenarios, and updated estimates of the costs of malaria treatment (Pandey 2010). In 2010, the average annual adaptation costs for treating diarrheal disease and malaria were estimated to be $3-5 billion, with the costs expected to decline over time with improvement in basic health services. Over the period 2010-2050, the average annual costs were estimated to be around $2 billion, with most of the costs related to treating diarrheal disease; the largest burden is expected to be in Sub-Saharan Africa.

The differences in costs from Ebi (2008) are primarily due to a reduction in the baseline burden of disease and lower costs for malaria treatment.

The malaria estimates from the global estimates of the costs of adaptation are comparable with estimates of the additional health care costs in 2025 in Southern Africa due to a climate change-related increase in the incidence of malaria (Van Rensburg and Blignaut 2002). Assuming low (high) cost scenarios, additional costs for the prevention and treatment of malaria in South Africa were estimated to be approximately $280 (3,764) million, or 0.23% of GDP, in 2025. Estimates for Botswana and Namibia are $ 9 (124) million and $ 13 (177) million, respectively. The high cost scenario for Namibia is about 4.6% of GDP.

(Bosello *et al.*, 2006) used a computable general equilibrium model to study the economic impacts of climate-change-induced changes in the mortality and morbidity due to cardiovascular and respiratory diseases, malaria, diarrhea, schistosomiasis, and dengue fever. They considered the effects on labor productivity and demand for health care, and found that health and welfare impacts have the same sign. The economy-wide health impacts were greater than simple aggregation of the costs of the individual health outcomes. Increased health problems were associated with an expansion of the public sector at the expense of the private sector.

Because any additional climate change-related cases are projected to occur primarily in low-income countries, where no or limited health care is provided by the government, the treatment costs will primarily be borne by families (WHO 2004). Time off from work to care for sick children would affect productivity.

The costs of cases of cholera in Tanzania due to climate change in 2030 were estimated to be in the range of 0.32 – 1.4 % of GDP (Trærup *et al.*, 2011), and the costs of treating additional cases of diarrhea and malaria in 2030 ranged from Rs. 3648–7787 lakhs, depending on the emission scenario (Ramakrishnan, 2011).

10.9. Impacts on Markets and Development

Prior sections of this chapter present the direct impacts of climate change on the economy sector by sector. There are, however, also indirect impacts. The effects that impacts in one sector may have on the rest of the economy are initially presented, followed by the impacts on economic growth and development.

10.9.1. General Equilibrium Effects

General equilibrium analysis describes how climate change impacts in one sector propagate to the rest of the economy, how impacts in one country influence other countries, and how macroeconomic conditions affect each impact (Ginsburgh and Keyzer, 1997). There are three channels through which impact diffuse. First, outputs of one sector are used as inputs to other sectors. For example, a change in crop yields would affect the food-processing industry. Second, products compete for the consumers' finite budget. If, for example, food becomes more expensive, less money would be spent on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If more labor is needed in agriculture to offset a drop in crop yields, less labor is available to produce other goods and services. Firms and households react to changes in relative prices, domestically and internationally. Ignoring these effects would lead to biased estimates of the impacts of climate change.

General equilibrium models can provide a comprehensive and internally consistent analysis of the medium-term impact of climate change on economic activity and welfare. However, these models necessarily make a number of simplifying assumptions, particularly with regard to the rationality of consumers and producers and the absence of market imperfections. Partial equilibrium models can be more detailed and more realistic.

Computable general equilibrium models have long been used to study the wider economic implications of changes in crop yields (Kane *et al.*, 1992). (Yates and Strzepek, 1998) show for instance that the impact of a reduced flow of the Nile on the economy of Egypt is much more severe without international trade than with, because trade would allow Egypt to focus on water-extensive production for export and import its food.

Older studies focused on the impact of climate change on patterns of specialization and trade, food prices, food security and welfare (Kane *et al.*, 1992; Reilly *et al.*, 1994; Winters *et al.*, 1998; Yates and Strzepek, 1998; Darwin and Kennedy, 2000; Darwin, 2004). This has been extended to land use (Lee, 2009; Ronneberger *et al.*, 2009), water use (Kane *et al.*, 1992; Calzadilla *et al.*, 2011), and multiple stresses (Reilly *et al.*, 2007). General equilibrium models have also been used to estimate the value of improved weather forecasts (Arndt and Bacou, 2000), a form of adaptation to climate change. Computable general equilibrium analysis has also been used to study selected impacts other than agriculture, notably sea level rise (Darwin and Tol, 2001; Bosello *et al.*, 2007), tourism (Berrittella *et al.*, 2006b; Bigano *et al.*, 2008b), human health (Bosello *et al.*, 2006) and energy (see 10.2).

(Bigano *et al.*, 2008b) study the joint impacts on tourism and coasts, finding that tourism dominates the welfare impacts. (Kemfert, 2002) and (Eboli *et al.*, 2010a) estimate the joint effect on the world economy of a range of climate change impacts, but conflate general equilibrium and growth effects. (Aaheim *et al.*, 2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian peninsula. They find positive impacts on output in some sectors (agriculture, electricity) negative impacts in other sectors (forestry, transport) and negligible ones in others (manufacturing, services). (Ciscar *et al.*, 2011) study the combined impact on agriculture, coasts, river floods and tourism in the current European economy. They find an average welfare loss of 0.2-1.0% of welfare but there are large regional differences with losses in Southern Europe and gains in Northern Europe.

The following initial conclusions emerge. First, markets matter. Impacts are transmitted across locations—with local, regional and global impacts-- and across multiple sectors of the economy. For instance, landlocked countries are affected by sea level rise because their agricultural land increases in value as other countries face erosion and floods. Second, consumers and producers are often affected differently. The price increases induced by a reduction in production may leave producers better off while hurting consumers. Third, the distribution of the direct impacts can be very different than the distribution of the indirect effects. For instance, a loss of production may be advantageous to an individual company or country if the competition loses more. Fourth, a loss of productivity or productive assets in one sector leads to further losses in the rest of the economy. Fifth, markets offer options for adaptation, particularly possibilities for substitution. This changes the size, and sometimes the sign of the impact estimate.

10.9.2. Growth Effects

10.9.2.1. The Rate of Economic Growth

Climate change would also affect economic growth and development, but our understanding is limited. (Fankhauser and Tol, 2005) investigate four standard models of economic growth and three transmission mechanisms: economic production, capital depreciation, and the labor force. They find that, in three models, the fall in economic output is slightly larger than the direct impact on markets while the 4th model (which emphasizes human capital accumulation) points to indirect impacts that are 1.5 times as large as the direct impacts. The difference can be understood as follows. In the three models, the impacts of climate change crowd out consumption and investment in physical capital, while in the fourth model investment in human capital too is crowded out; lower investment implies slower growth. (Hallegatte, 2005) reaches a similar conclusion. (Hallegatte and Thery, 2007; Hallegatte and Ghil, 2008; Hallegatte and Dumas, 2009) highlight that the impact of climate change through natural hazards on economic growth can be amplified by market imperfections and the business cycle. (Eboli *et al.*, 2010a) use a multi-sector, multi-region growth model. The impact of climate change would lead to a 0.3% reduction of GDP in 2050. Regional impacts are more pronounced, ranging from -1.0% in developing countries to +0.4% in Australia and Canada. Sectoral results are varied too, with output changes ranging from output of +0.5% for power generation (to meet increased demand to air conditioning) to -0.7% for natural gas (as demand for space heating falls) and rice.

Using a biophysical model of the human body's ability to do work, (Kjellstrom *et al.*, 2009b) find that by the end of the century climate change may reduce labor productivity by 11-27% in the humid (sub)tropics. Assuming a output elasticity of labor of 0.8, this would reduce economic output in the affected sectors (involving heavy manual labor

without air conditioning) by 8-22%. Although structural change in the economy may well reduce the dependence on manual labor and air conditioning would be an effective adaptation, even the ameliorated impact would have a substantial, but as yet unquantified, impact on economic growth.

There are also statistical analyses of the relationship between climate and economic growth. (Barrios *et al.*, 2010) find that the decline in rainfall in the 20th century partly explains the economies of Sub-Saharan Africa have grown more slowly than those of other developing regions. (Brown *et al.*, 2011) corroborate this. (Dell *et al.*, 2012) find that, in the second half of the 20th century, anomalously hot weather slowed down economic growth in poor countries, in both the agricultural and the industrial sectors. (Dell *et al.*, 2009) find that one degree of warming would reduce income by 1.2% in the short run, and by 0.5% in the long run. The difference is due to adaptation. (Horowitz, 2009) finds a much larger effect: a 3.8% drop in income in the long run for one degree of warming.

10.9.2.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one of the causes of poverty. (Gallup *et al.*, 1999) emphasize the link between climate, disease, and poverty while (Masters and McMillan, 2001) focus on climate, agricultural pests, and poverty. Other studies (Acemoglu *et al.*, 2001; Acemoglu *et al.*, 2002; Easterly and Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc) are accounted for. However, (Van der Vliert, 2008) demonstrates that climate affects human culture and thus institutions, but this has yet to be explored in the economic growth literature. (Brown *et al.*, 2011) find that weather affects economic growth in Sub-Saharan Africa – particularly, drought decelerates growth. (Jones and Olken, 2010) find that exports from poor countries fall during hot years. (Bloom *et al.*, 2003) find limited support for an impact of climate (rather than weather) on past growth in a single-equilibrium model, but strong support in a multiple-equilibrium model: Hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

(Galor and Weil, 1996) speculate about the existence of a climate-health-poverty trap. (Strulik, 2008; Bonds *et al.*, 2010; Bretschger and Valente, 2011; Ikefuji and Horii, 2012) posit theoretical models and offer limited empirical support, while (Tang *et al.*, 2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Gollin and Zimmermann, 2008; Bretscher and Valente, 2010; Gollin and Zimmermann, 2010; Ikefuji *et al.*, 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This leads to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that the investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change would thus trap more people in poverty.

(Zimmerman and Carter, 2003; Ikefuji and Horii, 2012) build a model in which the risk of natural disasters causes a poverty trap: At higher risk levels, households prefer assets with a safe but low return. (Carter *et al.*, 2007) find empirical support for this model at the household level, but (van den Berg, 2010) concludes the natural disaster itself has no discernible impact on investment choices. At the macro-economic level, natural disasters disproportionally affect the growth rate of poor countries (Noy, 2009).

(Devitt and Tol, 2012) construct a model with conflict-poverty trap, and show that climate change may exacerbate this. (Bougheas *et al.*, 1999; Bougheas *et al.*, 2000) show that more expensive infrastructure, for example because of frequent repairs after natural disasters, slows down economic growth and that there is a threshold infrastructure cost above which trade and specialization do not occur, suggesting another mechanism through which climate could cause a poverty trap. The implications of climate change have yet to be assessed.

10.9.2.3. Conclusion

In sum, the literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. There is disagreement whether climate change would affect the nature of economic development, with some studies suggesting that more people may be trapped in poverty and fewer people enjoying exponential growth.

10.10. Research Needs and Priorities

Evaluating the economic aspects of the impacts has emerged as an active research area. Initial work has developed in a few key economic sectors and through economy wide economic assessments. Data, tools and methods continue to evolve to address additional sectors and more complex interactions among the sectors in the economic systems and a changing climate.

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Multiple aspects of energy impacts have been assessed, but others remain to be evaluated, particularly economic impact assessments of adaptation both on existing and future infrastructure, but also the costs and benefits for future systems under differing climatic conditions. Studies focused on the impacts of climate change on the energy sector indicate both potential benefits and detrimental impacts across developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy related resource base, conversion and transport technologies.

The economics of climate change impacts on transportation systems and their role in overall economic activity have yet to be well understood. For water related sectors, improved estimation of flood damages to economic sectors, research on economic impacts of ecosystems, rivers, lakes and wetlands, ecosystems service, and tourism and recreation are needed. Economic assessments of adaptation strategies such as water savings technologies, particularly for semi-arid and arid developing countries, are also needed. Further, detailed studies are needed of the integrated impact of climate change on all water-dependent economic sectors, as existing studies do not examine competitiveness between water uses among sectors and economic productivity.

Although both tourism and recreation are sensitive to climate change, the literature on tourism is far more extensive. Current studies either have a rudimentary representation of the effect of weather and climate but a detailed representation of substitution between holiday destination and activities, or a detailed representation of the immediate impact of climate change but a rudimentary representation of alternatives to the affected destinations or activities.

Considerable research has been developed related to climate change and associated weather risk to insurance; however, limited research has been published on observed trends in normalized insured climate-related losses as compared to trends in direct economic climate-related losses, including insured property and agriculture losses as compared to direct economic losses. Additionally, no quantitative study could be found for projected impacts on health and life insurance, and only few on regional markets including scenarios on hazard, exposure, vulnerability and adaption status, regulation, risk capital availability. Furthermore, little is known regarding the temporal changes of vulnerability for insured risk such as how susceptibilities of structures to damage changed in the past and can be projected to change in the future.

Little literature exists on potential climate impacts on other economic sectors, such as mining, manufacturing, and services (apart from health, insurance and tourism); in particular assessments of whether these sectors are indeed sensitive to climate and climate change.

The spillover effects of the impacts of climate change in one sector on other markets are understood in principle, but the number of quantitative studies is too few to place much confidence in the numerical results. Similarly, the impact of climate and climate change on economic growth and development is not well understood, with some studies pointing to a small or negligible effect and other studies arguing for a large or dominant effect.

Frequently Asked Questions

FAQ 10.1: Why are key economic sectors vulnerable to climate change?

Many key economic sectors are impacted by changing climate conditions, related long term changes in temperature, precipitation, sea level rise, and extreme events. For example, in addition to many other purposes, energy is used to keep buildings warm in winter and cool in summer. A change in temperature would thus affect energy demand. Climate change affects energy supply, among others, through the cooling of thermal plant, though wind, solar and water resources, and through transport and transmission infrastructure. Water demand increases with temperature but falls with rising carbon dioxide concentrations. Water supply depends on precipitation patterns and temperature, and water infrastructure is vulnerable to extreme weather, while transport infrastructure is designed to withstand a particular range of weather conditions and climate change would expose this infrastructure to weather outside historical design criteria. Tourism is also affected by climate change, as most people prefer to spend part of their free time outdoors, be it hiking, skiing, or lazing on a beach in the sun. Climate change would lead people to enjoy themselves differently, at different times, and in different places. Health care systems are also impacted, as climate change affects a number of diseases and thus the demand for and supply of health care.

FAQ 10.2: How does climate change impact the financial services industry?

Insurance buys financial security against, among other perils, weather hazards. Climate change impacts, including increased weather variability, are anticipated to increase losses and loss variability in various regions through more frequent and/or intensive weather disasters. This will challenge insurance systems to offer coverage for premiums that are still affordable, while at the same time require more risk-based capital. Adequate insurance coverage will be challenging in low- and middle-income countries.

FAQ 10.3: Are other economic sectors vulnerable to climate change too?

Economic activities such as agriculture, forestry, fisheries and mining are exposed to the weather and thus vulnerable to climate change. Other economic activities, such as manufacturing and services, largely take place in controlled environments and are not really exposed to climate change. However, markets connect sectors so that the impacts of climate change spillover from one activity to all others. The impact of climate change on economic development and growth also affects all sectors.

Cross-Chapter Box

Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use ($kWhr/m^3$) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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Appendix 10.A1. Industrial Classification and Chapter Outline

International Standard Industrial Classification (ISIC) of All Economic Activities, Rev.4, the outline of Chapter 10, and nil returns in a literature search on Scopus.

- A - Agriculture, forestry and fishing (10.5)
  - 01 - Crop and animal production, hunting and related service activities
  - 02 - Forestry and logging
  - 03 - Fishing and aquaculture
- B - Mining and quarrying (10.5)
  - 05 - Mining of coal and lignite
  - 06 - Extraction of crude petroleum and natural gas
  - 07 - Mining of metal ores
  - 08 - Other mining and quarrying
    - Climate change impact & quarrying: No results*
  - 09 - Mining support service activities
- C – Manufacturing (10.5, except C19)
  - 10 - Manufacture of food products
    - Climate change impact & food products: No results*
    - Climate change impact & food processing: No results*
  - 11 - Manufacture of beverages
    - Climate change impact & beverages: No results*
  - 12 - Manufacture of tobacco products
    - Climate change impact & tobacco: No results*
  - 13 - Manufacture of textiles
    - Climate change impact & textiles: No results*
  - 14 - Manufacture of wearing apparel
    - Climate change impact & apparel: No results*
  - 15 - Manufacture of leather and related products

        - Climate change impact & leather: No results*
    - 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
        - Climate change impact & wood: No results*
    - 17 - Manufacture of paper and paper products
        - Climate change impact & pulp paper: No results*
    - 18 - Printing and reproduction of recorded media
        - Climate change impact & printing: No results*
        - Climate change impact & recorded media: No results*
    - 19 - Manufacture of coke and refined petroleum products (10.2)
    - 20 - Manufacture of chemicals and chemical products
        - Climate change impact & chemical production: No results*
    - 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
        - Climate change impact & pharmaceutical: No results*
    - 22 - Manufacture of rubber and plastics products
        - Climate change impact & rubber: No results*
        - Climate change impact & plastic: No results*
    - 23 - Manufacture of other non-metallic mineral products
        - Climate change impact & cement: No results*
        - Climate change impact & glass: No results*
    - 24 - Manufacture of basic metals
        - Climate change impact & steel: No results*
        - Climate change impact & iron: No results*
        - Climate change impact & alumina: No results*
        - Climate change impact & aluminum: No results*
    - 25 - Manufacture of fabricated metal products, except machinery and equipment
        - Climate change impact & metal: No results*
    - 26 - Manufacture of computer, electronic and optical products
        - Climate change impact & equipment: No results*
    - 27 - Manufacture of electrical equipment
        - Climate change impact & equipment: No results*
    - 28 - Manufacture of machinery and equipment n.e.c.
        - Climate change impact & equipment: No results*
        - Climate change impact & machinery: No results*
    - 29 - Manufacture of motor vehicles, trailers and semi-trailers
        - Climate change impact & vehicle: No results*
    - 30 - Manufacture of other transport equipment
        - Climate change impact & equipment: No results*
    - 31 - Manufacture of furniture
        - Climate change impact & furniture: No results*
    - 32 - Other manufacturing
    - 33 - Repair and installation of machinery and equipment
        - Climate change impact & equipment: No results*
        - Climate change impact & machinery: No results*
- D - Electricity, gas, steam and air conditioning supply (10.2)
    - 35 - Electricity, gas, steam and air conditioning supply
- E - Water supply; sewerage, waste management and remediation activities
    - 36 - Water collection, treatment and supply (10.3)
    - 37 – Sewerage (10.3)
    - 38 - Waste collection, treatment and disposal activities; materials recovery (10.8)
    - 39 - Remediation activities and other waste management services (10.8)
- F – Construction (10.5)
    - 41 - Construction of buildings
    - 42 - Civil engineering

- 43 - Specialized construction activities
- G - Wholesale and retail trade; repair of motor vehicles and motorcycles (10.8)
  - 45 - Wholesale and retail trade and repair of motor vehicles and motorcycles
  - 46 - Wholesale trade, except of motor vehicles and motorcycles
  - 47 - Retail trade, except of motor vehicles and motorcycles
- H - Transportation and storage (10.4)
  - 49 - Land transport and transport via pipelines
  - 50 - Water transport
  - 51 - Air transport
  - 52 - Warehousing and support activities for transportation
  - 53 - Postal and courier activities
- I - Accommodation and food service activities (10.6)
  - 55 - Accommodation
  - 56 - Food and beverage service activities
- J - Information and communication (10.8)
  - 58 - Publishing activities
  - 59 - Motion picture, video and television programme production, sound recording and music publishing activities
  - 60 - Programming and broadcasting activities
  - 61 - Telecommunications
  - 62 - Computer programming, consultancy and related activities
  - 63 - Information service activities
- K - Financial and insurance activities (10.7)
  - 64 - Financial service activities, except insurance and pension funding
  - 65 - Insurance, reinsurance and pension funding, except compulsory social security
  - 66 - Activities auxiliary to financial service and insurance activities
- L - Real estate activities (10.8)
  - 68 - Real estate activities
- M - Professional, scientific and technical activities (10.8)
  - 69 - Legal and accounting activities
  - 70 - Activities of head offices; management consultancy activities
  - 71 - Architectural and engineering activities; technical testing and analysis
  - 72 - Scientific research and development
  - 73 - Advertising and market research
  - 74 - Other professional, scientific and technical activities
  - 75 - Veterinary activities
- N - Administrative and support service activities (10.8 except N79)
  - 77 - Rental and leasing activities
  - 78 - Employment activities
  - 79 - Travel agency, tour operator, reservation service and related activities (10.6)
  - 80 - Security and investigation activities
  - 81 - Services to buildings and landscape activities
  - 82 - Office administrative, office support and other business support activities
- O - Public administration and defence; compulsory social security (10.8)
  - 84 - Public administration and defence; compulsory social security
- P – Education (10.8)
  - 85 - Education
- Q - Human health and social work activities (10.8)
  - 86 - Human health activities
  - 87 - Residential care activities
  - 88 - Social work activities without accommodation
- R - Arts, entertainment and recreation (10.6)
  - 90 - Creative, arts and entertainment activities
  - 91 - Libraries, archives, museums and other cultural activities

- 92 - Gambling and betting activities
- 93 - Sports activities and amusement and recreation activities

- S - Other service activities (10.8)
  - 94 - Activities of membership organizations
  - 95 - Repair of computers and personal and household goods
  - 96 - Other personal service activities
- T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use (10.8)
  - 97 - Activities of households as employers of domestic personnel
  - 98 - Undifferentiated goods- and services-producing activities of private households for own use
- U - Activities of extraterritorial organizations and bodies (10.8)
  - 99 - Activities of extraterritorial organizations and bodies

*No results = no results for the impact of climate change on this particular economic activity. There may be results for the impact of climate change on a related activity, or for the impact of the activity on climate change.

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Table 10-1: Main projected impacts of CC and EWEs on energy supply.

Tech	Changes in climatic or related attributes	Possible impacts	Adaptation options
Thermal and nuclear power plants	Increasing air temperature	Reduces efficiency of thermal conversion by 0.1-0.2% in the USA; by 0.1-0.5% in Europe where the capacity loss is estimated in the range of 1-2%/1°C temperature increase, accounting for decreasing cooling efficiency and reduced operation level/shutdown	Siting at locations with cooler local climates where possible
	Changing (lower) precipitation and increasing air temperature increases temperature and reduces the availability of water for cooling	Less power generation; annual average load reduction by 0.1-5.6% depending on scenario	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage); Re-use of process water from flue gases (can cover 25-37% of the power plants cooling needs), coal drying, condensers (dryer coal has higher heating value, cooler water enters cooling tower),, flue-gas desulphurization; Using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower; Condenser mounted at the outlet of cooling tower to reduce evaporation losses (by up to 20%). Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers; Costs of retrofitting cooling options depend on depend on features of existing systems, distance to water, required additional equipment, estimated at US$250,000-500,000/MW
	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency; limited cooling water discharge; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings (air conditioning) and of coal stockpiles (water spraying)
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual CC
Hydropower	Increase/decrease in average water availability	Increased/reduced power output	Schedule release to optimize income
	Changes in seasonal and inter-annual variation in inflows (water availability)	Shifts in seasonal and annual power output; floods and lost output in the case of higher peak flows	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity
	Extreme precipitation causing floods	Direct and indirect (by debris carried from flooded areas) damage to dams and turbines, lost output due to releasing water through by-pass channels	Soft: adjust water management Debris removal Hard: increase storage capacity
Solar energy	Increasing mean temperature	Improving performance of TH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5%/1°C temperature increase for crystalline Si and thin-film modules as well, but performance varies across types of modules, with thin film modules performing better; Long-term exposure to heat causes faster aging	

	Changing cloudiness	Increasing unfavourable (reduced output), decreasing beneficial (increased output) for all types, but evacuated tube collectors for TH can use diffuse insolation. CSP more vulnerable (cannot use diffuse light)	Apply rougher surface for PV panels that use diffuse light better; optimize fixed mounting angle for using diffuse light, apply tracking system to adjust angle for diffuse light conditions; Install/increase storage capacity
	Hot spells	Material damage for PV, reduced output for PV and CSP; CSP efficiency decreases by 3-9% as ambient temperature increases from 30 to 50°C and drops by 6% (tower) to 18% (trough) during the hottest 1% of time	Cooling PV panels passively by natural ail flows or actively by forced air or liquid coolants
	Hail	Material damage to TH: evacuated tube collectors are more vulnerable than flat plate collectors; Fracturing as glass plate cover, damage to photoactive material	Flat plate collectors: using reinforced glass to withstand hailstones of 35mm (all of 15 tested) or even 45 mm (10 of 15 tested); only 1 in 26 evacuated tube collectors withstood 45mm hailstones Increase protection to current standards or beyond them
Wind power	Windiness: total wind resource (multi-year annual mean wind power densities); *likely* to remain within ±50% of current values in Europe and North America; within ±25% of 1979-2000 historical values in contiguous USA	Change in wind power potential	Site selection
	Wind speed extremes: gust, direction change, shear	Structural integrity from high structural loads; fatigue, damage to turbine components; reduced output	Turbine design, lidar-based protection

Sources: (Nee Schulz, 2012),(Parkpoom *et al.*, 2005), (ADAM-Project, 2009),(NETL (National Energy Technology Laboratory), 2007; Feeley III *et al.*, 2008; Ott and Richter, 2008; Förster and Lilliestam, 2009; Hoffmann *et al.*, 2010; Linnerud *et al.*, 2011; Mukheibir, 2013; Williams, 2013), (Schaefli *et al.*, 2007; Markoff and Cullen, 2008),(Droogers, 2009). (EPA , 2001; Norton, 2006; Pryor *et al.*, 2006; Walter *et al.*, 2006; Christensen and Busuioc, 2007; DOE, 2007; Bloom *et al.*, 2008; Haugen and Iversen, 2008; Leckebusch *et al.*, 2008; Sailor *et al.*, 2008; Honeyborne, 2009; Kurtz *et al.*, 2009; SPF, 2009; Pryor and Barthelmie, 2010; Pryor and Schoof, 2010; Pryor and Barthelmie, 2011(b); Kurtz *et al.*, 2011; Patt *et al.*, 2013; Pryor and Barthelmie, 2013).
Notes: TH: thermal heating; PV: photovoltaic; CSP: concentrating solar power.

Table 10-2: Main impacts of CC and EWEs on pipelines and the electricity grid.

Tech	Changes in climatic or related attribute	Impacts	Adaptation options
Pipelines	Melting permafrost	Destabilizing pillars, obstructing access for maintenance and repair	Adjust design code and planning criteria, install disaster mitigation plans
	Increasing high wind, storms, hurricanes	Damage to offshore and onshore pipelines and related equipment, spills; lift and blow heavy objects against pipelines, damage equipment	Enhance design criteria, update disaster preparedness
	Flooding caused by heavy rain, storm surge or sea-level rise	Damage to pipelines, spills	Siting (exclude flood plains), water proofing
Electricity grid	Increasing average temperature	Increased transmission line losses	Include increasing temperature in the design calculation for maximum temperature/rating
	Increasing high wind, storms, hurricanes	Direct mechanical damage to overhead lines, towers, poles, substations, flashover caused by live cables galloping and thus touching or getting too close to each other; indirect mechanical damage and short circuit by trees blown over or debris blown against overhead lines	Adjust wind loading standards, reroute lines alongside roads or across open fields, vegetation management, improved storm and hurricane forecasting
	Extreme high temperatures	Lines and transformers may overheat and trip off; flashover to trees underneath expanding cable	Increase system capacity, increase tension in the line to reduce sag, add external coolers to transformers
	Combination of low temperature, wind and rain, ice storm	Physical damage (including collapse) of overhead lines and towers caused by ice build-up on them	Enhance design standard to withstand larger ice and wind loading, reroute lines alongside roads or across open fields, improve forecasting of ice storms impacts on overhead lines and on transmission circuits

Sources: (Bayliss, 2007; Krausmann and Mushtaq, 2008; Reed, 2008; Hines *et al.*, 2009; Winkler *et al.*, 2010; Cruz and Krausmann, 2013),(Vlasova and Rakitina, 2010), (Ward, 2013), (McColl, 2012).

Table 10-3: Economy-wide implications of impacts of climate change and extreme weather on the energy sector.

Study	Model Type	Climate Impacts Modelled	Energy/Economic Impacts	Regions	Sectors Studied
(Bosello *et al.*, 2009)	IAM	Rising temperatures/ changing demand for energy; impacts from 4 other sectors/events (Global, 2001 - 2050)	Change in GDP in 2050 due to rising temperatures and changing energy demand: 0% to 0.75% (+1.2°C); -0.1% to 1.2% (+3.1°C)	14	4
(Jorgenson *et al.*, 2004)	CGE	Rising temperatures/ changing demand for energy; climate impacts from 3 other sectors (USA, 2000 - 2100)	Optimistic adaptation: 4% to 6.7% higher energy productivity per year (2000 – 2100); Output from electricity: -6% in 2050; GDP is +0.7% (aggregate all sectors, avg annual 2000 – 2100) Pessimistic adaptation: 0.5% to 2.2% lower energy productivity per year; Output from electricity: +2% in 2050; GDP is -0.6% (aggregate impact all sectors)	1	35
(Bosello *et al.*, 2007)	CGE	Rising temperatures/ changing demand for energy (Global, 2050)	Change in GDP in 2050 (perfect competition): -0.297% to 0.027%; Change in GDP in 2050 (imperfect competition): -0.303% to 0.027%	8	1
(Aaheim *et al.*, 2009)	CGE	Change in precipitation -> share of hydro power; rising temperatures/ changing demand for energy ; impacts from 4 other sectors (Western Europe, 2071 – 2100)	Impact from all sectors in 2100: GDP in cooler regions: -1% to -0.25% GDP in warmer regions: -3% to -0.5% Adaptation can mitigate 80% to 85% of economic impact	8	11
(Boyd and Ibarraran, 2009)	CGE	Drought scenario affecting hydro plus 3 other sectors (Mexico, 2005 - 2026)	Generation output in 2026: -2.1% Refining output: -10.1% Coal output: -7.8% NG output: -2% Crude oil output: +1.7% GDP: -3% With adaptation: Generation output in 2026: 0.24%% Refining output: 1.36%% Coal output: 1.09%% NG output: 0.34%% Crude oil output: 0.22% GDP: 0.33%	1	2
(Jochem *et al.*, 2009)	PE/ CGE	Rising temperatures/ changing demand for energy; Change in technical potential of renewables; Change in rainfall -> change in hydro; High temperatures -> water temperatures exceeding regulatory limits (Europe); High temperatures -> greater electric grid losses and lower thermal efficiency; generic extreme events -> reduced capital stock in CGE model (EU27+2, 2005 – 2050)	GDP (Europe): -50 billion € p.a. in 2035 GDP (Europe): -240 billion € p.a. in 2050 GDP (EU regions): -0.1% to -0.4% in 2035 GDP (EU regions): -0.6% to -1.3% in 2050 Jobs (Europe): -380K in 2035 Jobs (Europe): -1 million in 2050	25	1
(Eboli *et al.*, 2010b)	CGE	Rising temperatures/ changing demand for energy; climate impacts	By 2100, change in GDP due to climate impacts on energy	8	17

		in 4 other sectors modelled (Global, 2002 - 2100)	demand vary by country between ~ -0.15% and 0.7%. USA and Japan were negative and all other countries positive. Overall economic impact from all sectors is neutral to positive for developed countries and negative for developing.		
(Golombek *et al.*, 2011)	PE	Rising temperatures/ changing demand for energy; Rising temp/ reduced thermal efficiency; change in water inflow (Western Europe, 2030)	Net impact on the price of electricity is a 1% increase. Generation decreases by 4%	13	4
(Bye *et al.*, 2006)	PE	Water shortages (Nordic countries, hypothetical 2 year period)	Water shortage scenarios can lead to a 100% increase in electricity prices at peak demand over a 2 year period. Higher prices lead to marginal reductions in demand (~ 1% - 2.25%).	4	1
(Koch *et al.*, 2012)	PE	High temperatures -> water temperatures exceeding regulatory limits (Berlin, 2010 - 2050)	Thermal plant outages amounting to 60 million EURO for plants in Berlin through 2050	1	1
(Gabrielsen *et al.*, 2005)	Econo metric	Rising temperatures/ changing demand for energy; change in water inflow; change in wind speeds (Nordic countries, 2000 - 2040)	Net change in electricity supply in 2040: 1.8%. Change in electricity demand: 1.4%. Change in electricity price: -1.0%	4	1
(DOE, 2009)	PE	Drought scenario (Western Electric Coordinating Council, USA, 2010 – 2020)	In 2020, 3.7% reduction in coal generation; 43.4% increase in NG gen; 29.3% reduction in hydro gen. Production cost increase of $3.5 billion. Average monthly electricity prices up 8.1% (Nov) to 24.1% (Jul).	1	1

Note: The regions indicated in the ‘Regions’ column vary in size and are model-specific.

Table 10-4: Observed normalized insured losses from weather hazards.

Region / peril accounted for in normalized insured losses	Observation period	Trend (aggregation mode)	References
World / all weather-related	1990-2008	No trend (annual aggregates)	[1]
Australia / aggregate of bushfire, flood, hailstorm, thunderstorm, tropical cyclone	1967-2006	No trend (annual aggregates)	[7]
Germany / all weather-related Germany / floods Germany / convective events Germany / winter storms	1980-2008 1980-2008 1980-2008 1980-2008	Positive trend (annual aggregates) No trend (annual aggregates) No trend (annual aggregates) Positive trend (annual aggregates)	[1]
Southwest Germany / hailstorm	1986-2004	Positive trends in annual frequency of days exceeding thresholds of damage claim counts. Increase in annual count of hail damage claims.	[8]
Spain / floods	1971-2008	No trend (annual aggregates)	[2]
USA / winter storms (ice storms, blizzards and snow storms)	1949-2003	Positive trend (pentade totals) Positive trend (average loss per state, pentade totals)	[3]
USA / all flood ("flood only" and floods specifically caused by convective storms, tropical cyclones, snow-melt)	1972-2006	Positive trend (annual aggregates)	[4]
USA / tropical cyclones	1949-2004	Increase (7-year totals) No statistical trend assessment.	[5]
USA / hailstorm	1951-2006	Focus on top-ten major hail storm losses of the period 1951-2006. Increase in frequency and loss in the 1992-2006 period as compared to 1951-1991. No statistical trend assessment.	[6]
USA east of 109° W / convective events (hail, heavy precipitation and flash flood, straight-line wind, tornado)	1970-2009 March to September	Standard deviation (variability) by 65% greater for 1990-2009 than for 1970-1989. Mean annual loss by 167% greater for 1990-2009 than for 1970-1989. Data: normalized insured loss exceeding US$ 150 million per event, annual aggregates.	[9]
USA / all weather-related USA / floods USA / convective events USA / winter storms USA / tropical cyclones USA / heat episodes USA / cold spells	1973-2008 1973-2008 1973-2008 1973-2008 1973-2008 1973-2008 1973-2008	Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) No trend (annual aggregates)	[1]

References: [1] (Barthel and Neumayer, 2012); [2] (Barredo *et al.*, 2012); [3] (Changnon, 2007); [4] (Changnon, 2008); [5] (Changnon, 2009a); [6] (Changnon, 2009b); [7] (Crompton and McAneney, 2008); [8] (Kunz *et al.*, 2009); [9] (Sander *et al.*, planned 2013).

Table 10-5: Climate change projections of insured losses and/or insurance prices.

Hazard/ insurance line	Region	Changes in future time slice(s) relative to current or control climate*			
Winter storm/ Homeowners' insurance**		2021-2050	End of 21st century		[4] [5]
	Europe in general	-	+44% A2 [18]		[13]
	France	+2% to +9% A1B [5]	+6% to +47% A1B, A2 [5;14;18]		[14]
	Belgium/Netherlands	+4% to +7% A1B [5]	+8% to +80% A1B, A2 [5;18]		[15]
	UK/Ireland	+6% to +13% A1B [5]	+17% to +43% A1B, A2 [4;5;13;14;18]		[18]
	Sweden/Norway	-	+7% to +95% A1B, A2 [14;18]		
	Germany	+5% to +18% A1B [5]	+15% to +114% A1B, A2 [5;13;14;18]		
	North Rhine-Westphalia	-	+8% to +19% A1B, A2 [15]		
	Switzerland	-	+19% A2 [18]		
	Poland	+2% to +12% A1B [5]	-23% to +12% A1B, A2 [5;18]		
	Portugal/Spain	-4% to -2% A1B [5]	-10% to -5% A1B, A2 [5;14]		
Winter storm/ Homeowners' insurance**	Germany	2011-2040	2041-2070		[7]
		+1.2% A1B	+17% A1B		
Winter storm/ Homeowners' insurance**		End of 21st century			[16] [18]
	Europe in general	RP shift: 5 2.7, 10 5.1, 20 9.5, A2 [16] Return level change: RP10: +23%, RP30: +50%, RP100: +104%, A2 [18]			
	France	RP shift: 5 2.5, 10 4.3, 20 7.4, A2 [16]			
	Belgium	RP shift: 5 2.5, 10 4.6, 20 8.5, A2 [16]			
	Netherlands	RP shift: 5 2.6, 10 4.9, 20 9.1, A2 [16]			
	UK	RP shift: 5 3.2, 10 6.6, 20 13.9, A2 [16]			
	Ireland	RP shift: 5 4.1, 10 8.2, 20 16.1, A2 [16]			
	Norway	Significant lengthening of RPs: 1 – 2, A2 [16]			
	Denmark	RP shift: 5 2.9, 10 5.6, 20 10.9, A2 [16]			
	Germany	RP shift: 5 2.7, 10 4.6, 20 7.7, A2 [16]			
Winter storm/ Homeowners' insurance**	Germany	2011-2040 Return level change: RP10: +6% to +35% RP25: -10% to +26% RP50: -23% to +23%	2041-2070 Return level change: RP10: +20% to +30% RP25: +5% to +41% RP50: -8% to +50%	2071-2100 Return level change: RP10: +40% to +45% RP25: +45% to +58% RP50: +50% to +55%	[10]
		Ensemble of three downscaling approaches, A1B: dynamical, dynamical-statistical, and statistical.		Two downscaling approaches, A1B: dynamical and dynamical-statistical.	
Winter storm and hailstorm/ Homeowners' insurance**	Germany	2011-2040 +6% A1B Return level change: RP10: +12%, RP20: +12%, RP50: +9%	2041-2070 +26% A1B Return level change: RP10: +19%, RP20: + 6%, RP50: - 7%		[7]
Hailstorm/ Homeowners' insurance**	Germany	2011-2040 +15% A1B	2041-2070 +47% A1B		[7]
Hailstorm/ Agricultural insurances**	Netherlands	2050s, i.e. +1°C (+2°C) global mean temperature Outdoor farming insurance +25% to +29% (+49% to +58%) Greenhouse horticulture insurance +116% to +134% (+219% to +269%)			[2]
Hurricane/ All insurance lines affected by tropical cyclone	USA	End of 21st century ECHAM5/MPIOM A2: RP shift: 10 13, 20 30, 50 130 MRI/JMA A1B: RP shift: 10 7.7, 20 16, 50 52 (contrarious model results render loss estimates impossible)			[17]

damages**					
Hurricane/ Homeowners' insurance***	Florida/USA	Insurance price level change (strained reinsurance capacity):			[12]
		2020s -20% to +5% (current adaptation)	2040s -28% to +10% (current adaptation)		
		Upgrade to full adaptation (85% of homes meet FL Building Code 2004):			
		-61% to -51%	-66% to -44%		
Typhoon/ Property insurance**	China	+2°C global mean temperature (2040s according to A1B/A2): +20%. Return level change: RP100: +7%, RP200: +14%.	+4°C global mean temperature (2070s according to A1FI): +32%. Return level change: RP100: +9%, RP200: +17%.		[4]
River flood/ Homeowners' flood insurance**	Germany	2011-2040 +84% [8] RP shift: 50 25 [6]	2041-2070 +91% [8] RP shift: 50 17 [6]	2071-2100 +114% [8] RP shift: 50 17 [6]	[6] [8]
		Seven member dynamical downscaling ensemble (B1,A1B,A2)			
Flood/ Property insurance (assumed)**	The Netherlands	2040 +125% relative to 2015 (corresponding to +24cm SLR)	2100 +1,784% relative to 2015 (corresponding to +85cm SLR)		[1]
Flood/ Property insurance**	United Kingdom	+2°C global mean temperature (2040s according to A1B/A2) +8%. Return level change: RP100: +18%, RP200: +14%.	+4°C global mean temperature (2070s according to A1FI) +14%. Return level change: RP100: +30%, RP200: +32%.		[4]
Rainfall, melting snow/ Homeowners' insurance**	Transect of three counties across southern Norway (Akershus, Buskerud, Hordaland)	End of 21st century +10% to +21% A2 +17% to +32% B2			[9]
Rainfall/ property and business interruption insurances**	Four city areas in Ontario, Canada (Ottawa, Toronto, Kitchener-Waterloo, London)	2016-2035 +13%	2046-2065 +20%	2081-2100 +30%	[3]
		Five member ensemble comprising IS92a, A2/B2, A2 scenarios			
Climate-related storms, pests, diseases/ Paddy rice insurance**	Japan	End of 21st century Paddy rice insurance payouts will decrease by 13%, on the basis of changes in standard yield and yield variability.			[11]

*Percentages indicate changes in mean annual loss ratio or absolute loss. For confidence intervals see the publications. Return period (RP) shifts identify changes in return period per loss level, return level changes identify changes in loss level per return period. RP<years>, e.g. RP100, denotes the return period of length <years>, e.g. 100 years.

**Spatial distribution and damage susceptibility of insured values assumed to be unchanged over time.

***Spatial distribution of insured values assumed to be unchanged over time; change of damage sensitivity possible.

References: [1] (Aerts and Botzen, 2011); [2] (Botzen *et al.*, 2010b); [3] (Cheng *et al.*, 2012); [4] (Dailey *et al.*, 2009); [5] (Donat *et al.*, 2011); [6] (German Insurance Association, 2011); [7] (Gerstengarbe *et al.*, 2013); [8] (Hattermann *et al.*, planned 2013); [9] (Haug *et al.*, 2011); [10] (Held *et al.*, planned 2013); [11] (Iizumi *et al.*, 2008); [12] (Kunreuther *et al.*, 2012); [13] (Leckebusch *et al.*, 2007); [14] (Pinto *et al.*, 2007); [15] (Pinto *et al.*, 2009); [16] (Pinto *et al.*, 2012); [17] (Raible *et al.*, 2012); [18] (Schwierz *et al.*, 2010).

Table 10-6: Supply-side challenges and sensitivities.

Challenges that increase in the climate change context	Example / Explanation
Failure to reflect temporal changes in hazard condition in risk management	After the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequence of the upswing and peak in hurricane activity: One insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas [9].
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) allows for a vicious circle of built-up areas already existing within flood plains pressing authorities to construct or improve protecting levees which in turn lead to even more development attracted by NFIP premium discounts, although exposed to extreme flooding events [11;20] [(IPCC, 2012)]. Additionally, older properties situated within flood plains and accounting for 16% of losses in the period 1978-2008 pay premiums substantially below the risk-adequate level [1;6;7;11;13;14]. These features represent incentives to not reduce individual flood risk adequately. Policy holders residing in flood plains where flood cover was made precondition for mortgage drop the cover after only two to four years, accounting for missing insurance penetration and insufficient built-up of NFIP risk capital [11;13;14]. All these features, together with some others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$ 20bn after the big hurricanes of 2006 [6;7;13;14].
Non-quantifiable uncertainties increasing risk	There is ambiguity as to what degree climate change may modify regional weather hazards – model projections are not unequivocal [2;3], and there is uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g. to extend claims payments beyond the original coverage [9]. Such uncertainties materialize in risk-based capital loadings [12].
Liability insurance impacted by new climate risk	Chances for success of litigation in the USA where damages from greenhouse gas emissions are sought seem small, due to legal obstacles [4;5;8;17], although fractional emissions allocation schemes and theories of continuous damage triggering are being discussed [16;19]. But defense costs can be high and may be covered by liability insurance [19]. As CO_2 emissions were declared pollution (US Supreme Court/EPA), regulation on limits for CO_2 emissions is ongoing and non-compliance could impose liability for CO_2 emissions in the near future, which will be covered by liability insurance. This pending risk has not yet been adequately taken into account, as was the case with escalating environmental liability claims in the late twentieth century [10;15]. The Supreme Court of Virginia ruled on 20 April 2012 that the intentional emissions of greenhouse gases by a specific energy company according to the plaintiffs contributed to global warming and damages such as that suffered by the Inupiat village of Kivalina. Hence, this damage could not be viewed as accident and would therefore not be covered by liability insurance [18].

References: [1] (Burby, 2006) [2] (Charpentier, 2008); [3] (Collier *et al.*, 2009); [4] (Ebert, 2010); [5] (Faure and Peeters, 2011); [6] (GAO, 2010); [7] (GAO, 2011); [8] (Gerrard, 2007); [9] (Grace and Klein, 2009); [10] (Hecht, 2008); [11] (Kousky and Kunreuther, 2010); [12] (Kunreuther *et al.*, 2009); [13] (Michel-Kerjan, 2010); [14] (Michel-Kerjan and Kunreuther, 2011); [15] (Mills, 2009); [16] (Patton, 2011); [17] (Stewart and Willard, 2010); [18] (Supreme Court of Virginia, U.S.A., 2012); [19] (Taylor and Tollin, 2009); [20] (Zahran *et al.*, 2009).

Table 10-7: Products and systems responding to changes in weather risks.

Response option	Example/Explanation
Risk-adjusted premiums convey the risk to the insureds, encouraging them to adaptive measures	Insurance flood hazard zoning systems, e.g. HORA (Austria), SIGRA (Italy), and ZÜRS (Germany), hamper development in high-risk zones that lead to higher premiums [23]. Prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households [37].
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options [24;39]; share of the insured in claims payment by deductibles or upper coverage limits, and exclusion of systematically affected property [1;6;7;8;9;12;18;37]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures [24;25;33]. The latter is contested by modelled high risk capital requirements and ambiguity loadings, rendering multiyear policies relatively expensive and less flexible for the insurance market [31].
Amplifying factors in large disaster losses included in risk models	Evacuation and systemic economic catastrophe impacts, adversely affecting regional workforce and repair capacity, or knock-on catastrophes following initial catastrophes, e.g. long-term flooding following hurricane landfall [35].
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitisation instruments, e.g. catastrophe bonds, industry loss warranties and sidecars, acquired greater prominence, and have been recovering again from the market break in 2008 [13;15;17]. Investors in insurance linked securities are attracted by the lack of correlation to typical financial market risks (e.g., currency risks), and the well defined loss-per-index structure. The higher transparency relative to other asset-backed securities, such as mortgage-backed securities, contributed to the better performance of catastrophe bonds following the financial crisis of 2007/2008 [13;15]. As bonds typically cover large losses, the basis risk, i.e. suffering damage without parametric triggering, is not substantial [38]; further reduction may be feasible by optimizing index measurements [13]. Weather derivatives are further instruments used to transfer risks to the capital markets [14;27;34]. Also multiple-trigger "hybrid" products are available, combining a parametric trigger-based catastrophe bond with a trigger-based protection against a simultaneous drop in stock market prices, thereby hedging against a double hit from direct disaster loss and losses incurred by the asset management side [4;15;28].
Index-based weather crop insurance products	Agricultural insurances predominantly cover crop, but also livestock, forestry, aquaculture, and greenhouses. Main products are indemnity-based crop insurance (covers for single perils and multiple peril events), and index-based crop insurance [36]. The latter is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation in India and Mexico [20;30]. Risk-based price signals may better foster adaptation if schemes are coupled with access to advanced technology, e.g. drought-resistant seed [3;12;20;30]. Various index definitions (cumulative rainfall, area-yield, etc.) and applications exist or have been proposed [3;26;27;29]. Adjusting to uncertain regional changes in temporal hazard condition is a basic challenge with climate change [11;21;26].
Improvements in index-based weather insurance	Basis risk can be reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential (e.g., based on a sample) and/or to the uppermost disaster risk layer only [11;12;19]. It can be better absorbed if index insurance works at aggregate level, e.g. to cover crop-credit portfolios or cooperatives, and if satellite-based remote-sensing technology can once be used to establish plot identification, yield estimation and loss assessment [19]. Pooling local schemes across climate regions under one cooperative parent organization, thus realizing central management, economics of scale and risk diversification, can reduce capital requirements and advance performance [5;10;32]. The disaster risk layer and high start-up costs (weather-data collection, risk modelling, education) necessitate subsidies from the state or donors [12;30].
Sovereign insurance schemes	Economic theory about the public sector's risk neutrality argues (i) that risks borne publicly render the social cost of risk-bearing insignificant and (ii) that disaster loss is seen small in comparison with a government's portfolio of diversified assets [2]. This theory proved inadequate if applied to relatively vulnerable small-sized middle to low-income countries [16], thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, that pools states, the reduction in premium cost per country is expected to be 45–50% [29]. Pooling natural catastrophe risks across an array of megacities has also been proposed, but not yet implemented [22].

References: [1] (Aakre *et al.*, 2010); [2] (Arrow and Lind, 1970) [3] (Barnett *et al.*, 2008) [4] (Barrieu and Loubergé, 2009) [5] (Biener and Eling, 2012); [6] (Botzen and van den Bergh, 2008) [7] (Botzen and van den Bergh, 2009) [8] (Botzen *et al.*, 2009) [9] (Botzen *et al.*, 2010a) [10] (Candel, 2007); [11] (Clarke and Grenham, 2012); [12] (Collier *et al.*, 2009); [13] (Cummins, 2012); [14] (Cummins and Mahul, 2009); [15] (Cummins and Weiss, 2009); [16] (Ghesquiere and Mahul, 2007); [17] (Guy Carpenter, 2011); [18] (Hecht, 2008); [19] (Herbold, planned 2013); [20] (Hess and Hazell, 2009); [21] (Hochrainer *et al.*, 2010); [22] (Hochrainer and Mechler, 2011); [23] (Kron, 2009); [24] (Kunreuther *et al.*, 2009); [25] (Kunreuther and Michel-Kerjan, 2009); [26] (Leblois and Quirion, 2011); [27] (Leiva and Skees, 2008); [28] (Leurig, 2011); [29] (Linnerooth-Bayer and Mechler, 2009); [30] (Mahul and Stutley, 2010); [31] (Maynard and Ranger, 2012); [32] (Meze-Hausken *et al.*, 2009); [33] (Michel-Kerjan and Kunreuther, 2011); [34] (Michel-Kerjan and Morlaye, 2008); [35] (Muir-Wood and Grossi, 2008); [36] (Swiss Re, 2013a); [37] (Thieken *et al.*, 2006) [38] (Van Nostrand and Nevius, 2011); [39] (Ward *et al.*, 2008);.

Table 10-8: Governance, public-private partnerships, and insurance market regulation.

Structural element	Example/Explanation
Public-private arrangements involving government intervention on the non-diversifiable disaster risk portion	Systems with government intervention range from ex ante risk financing design, such as public monopoly natural hazard insurance (e.g. Switzerland, with inter-cantonal pool) or compulsory forms of coverage to maximize the pool of insureds (e.g. Spain, France, with unlimited state guarantee on top), to ex post financing design, such as taxation-based governmental relief funds (e.g. Austria, Netherlands). In between these boundaries rank predominantly private insurance markets, in several countries combined with governmental post-disaster ad hoc relief (e.g. Germany, Italy, UK, Poland, USA) [16]; see also [1;4;5;13;14;15;18].
Care for people who cannot afford insurance (any more)	Either by funds outside the insurance system, e.g. insurance vouchers [8], or by premium subsidies (particularly for the catastrophic risk portion) [1;8;18;20].
Public-private partnership to expedite agricultural development	Insurance improve the farmers' creditworthiness that in turn strengthens their adaptive capacity. For instance, by means of loans farmers can step from low-yield to higher-yield cropping systems [3;9;10].
Proposals for adaptation-oriented climate change risk management frameworks to UNFCCC	Risk prevention and risk reduction is the starting point (AOSIS, Switzerland and MCII) that can absorb many of the smaller weather risks, and various forms of insurance are meant to cover all of the remaining risks [2;9;11;12;17;19]. The global framework, where the wealthy agree to pool risks with the most vulnerable, equals social insurance that is different from a risk-based share in insurance funds [6].

References: [1] (Aakre *et al.*, 2010); [2] (AOSIS, 2008); [3] (Barnett *et al.*, 2008); [4] (Botzen and van den Bergh, 2008); [5] (Bruggeman *et al.*, 2010); [6] (Duus-Otterström and Jagers, 2011); [7] (Kovacevic and Pflug, 2011); [8] (Kunreuther *et al.*, 2009); [9] (Linnerooth-Bayer *et al.*, 2009); [10] (Mahul and Stutley, 2010); [11] (MCII, 2008); [12] (MCII, 2012); [13] (Monti, 2012); [14] (Paudel, 2012); [15] (Schwarze and Wagner, 2007); [16] (Schwarze *et al.*, 2011); [17] (Swiss Confederation, 2008); [18] (Van den Berg and Faure, 2006); [19] (Warner and Spiegel, 2009); [20] (Zhu, 2011).

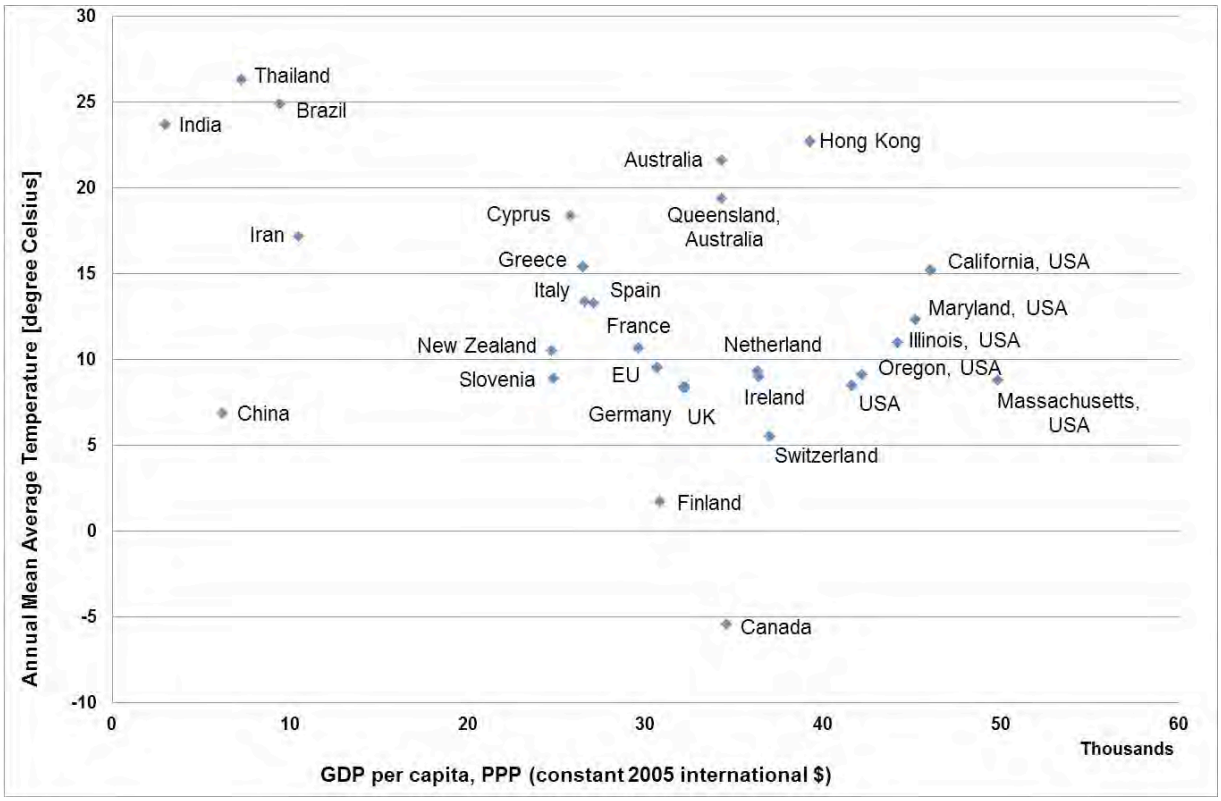

Figure 10-1: GDP per capita (in 2009) and annual mean temperature (based on 1971-2000 climatology) in selected countries and US federal states. Source: Toth, (2013). Note: PPP: purchasing power parity.

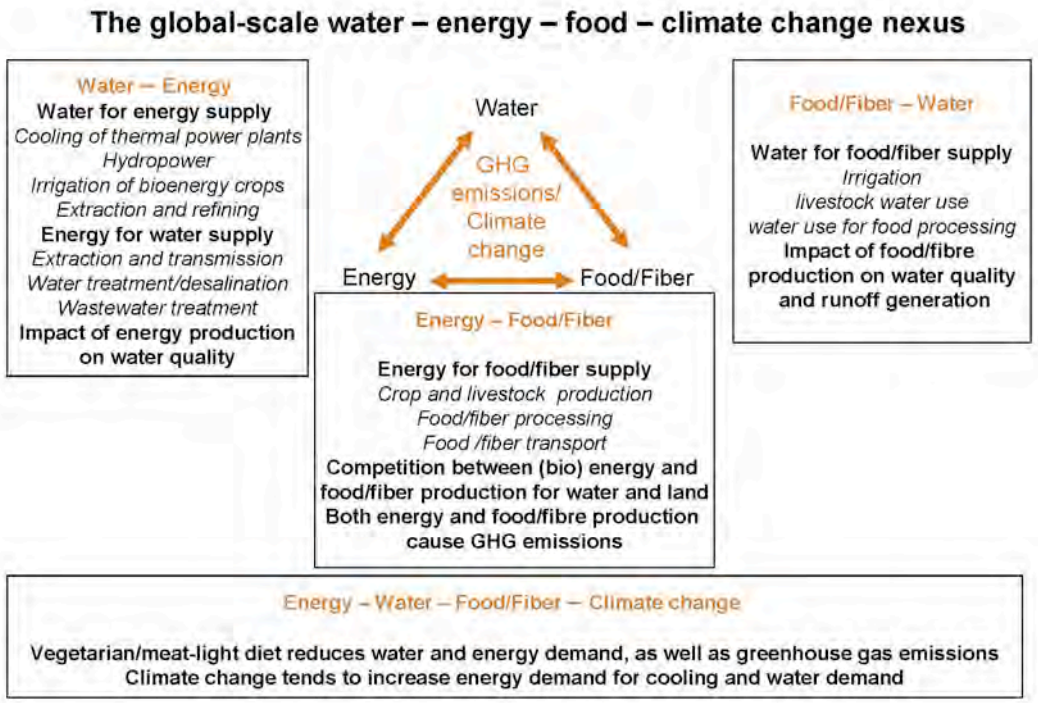

Figure WE-1: The water-energy-food nexus as related to climate change.

Chapter 11. Human Health

Coordinating Lead Authors
Kirk R. Smith (USA), Alistair Woodward (New Zealand)

Lead Authors
Diarmid Campbell-Lendrum (WHO), Dave Chadee (Trinidad and Tobago), Yasushi Honda (Japan), Qiyong Liu (China), Jane Olwoch (South Africa), Boris Revich (Russian Federation), Rainer Sauerborn (Sweden)

Contributing Authors
Helen Berry (Australia), Colin Butler (Australia), Lara Cushing (USA), Kristie Ebi (USA), Tord Kjellstrom (New Zealand), Sari Kovats (UK), Graeme Lindsay (New Zealand), Erin Lipp (USA), Tony McMichael (Australia), Virginia Murray (UK), Osman Sankoh (Sierra Leone), Marie O'Neill (USA), Seth Shonkoff (USA), Shelby Yamamoto (Germany)

Review Editors
Ulisses Confalonieri (Brazil), Andrew Haines (UK)

Volunteer Chapter Scientists
Zoë Chafe (USA), Joachim Rocklov (Germany)

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11.3: Who is most affected by climate change?
11.4: What is the most important adaptation strategy to reduce the health impacts of climate change?
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References

Executive Summary

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changing incidence in temperature and humidity extremes and occurrence of floods, storms, droughts, and fires. Indirectly, health may be damaged by ecological disruptions brought on by climate change (crop failures, shifting patterns of disease vectors), or social responses to climate change (such as displacement of populations following prolonged drought). Variability is a risk factor in its own right – it is more difficult to protect human health in a highly variable climate than one that is more stable. There is emerging evidence of non-linearities in response (such as greater-than-expected mortality due to heat waves) as climates become more extreme. [11.3, 11.5]

The most important effect of climate change is that it will exacerbate current risks to health. *[very high confidence]* Although new infections and other conditions may emerge under climate change *[low confidence],* the largest risks by far will apply in populations already most affected by climate-related diseases. Thus, for example, the risks of under-nutrition from climate change will fall mainly on populations already experiencing under-nutrition. [11.3]

The most effective adaptation measures for health in the immediate term, therefore, are programs that extend basic public health measures and essential health services, increase capacity for disaster preparedness and response, and alleviate poverty. [11.6] *[very high confidence*]

In recent decades, climate change has contributed to levels of ill-health (*likely*) though the present world-wide burden of ill-health from climate change is relatively small compared with other stressors on health and is not well quantified. Changes in temperature, rainfall and sea-level have altered distribution of some disease vectors, increased heat wave casualties, and reduced food production for vulnerable populations. *[moderate confidence]* [11.4]

If climate change continues as projected in scenarios in the next few decades, the major increases of ill-health compared to no climate change will occur through:

- Greater incidence of injury, disease, and death due to more intense heat waves, storms, floods, and fires. [11.4] *[very high confidence]*
- Increased risk of under-nutrition resulting from diminished food production in poor regions. [11.6] *[high confidence]*
- Loss of work capacity and reduced labor productivity in vulnerable populations [11.6] *[high confidence]*
- Increased risks of food- and water-borne diseases and vector-borne infections. [11.5] *[high confidence]*
- Modest improvements in some areas due to lower impacts of cold, shifts in food production, and reduction of disease-carrying vectors. These positive effects will be out-weighed, world-wide, by the magnitude and severity of the negative effects of climate change. [11.5] *[high confidence]*
- Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development *[high confidence],* particularly among the poorest and least healthy groups *[very high confidence]* [11.7]

In addition to their implications for climate change, essentially all the important Climate Altering Pollutants (CAPs) other than CO_2 have near-term health implications *[very high confidence*]. In 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants [*high confidence*], accounting potentially for an economic impact of 1-2 trillion USD , depending on the economic valuation method used *[low confidence*]. [Box 11-4]

In the highest IPCC Representative Concentration Pathway, RCP8.5, by 2100 most of the world land area will be experiencing 4-7 degree higher temperatures than the recent past due to anthropogenic climate change. This means that important tipping points for health impacts may have been exceeded in many areas of the world during this century. These include sea level rise, storms, loss of agricultural productivity, and daily temperature/humidity conditions that exceed coping mechanisms, making potentially large areas seasonally uninhabitable for normal human activities, including growing food or working outdoors. [11.8] *[high confidence]*

There are opportunities to both reduce emissions of CAPs and at the same time improve local health in the communities that take action – in addition to the health protection for populations worldwide from climate change abatement. Among others, mitigation-related actions that will return health co-benefits as well include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy production and use in households and communities, through better combustion, energy efficiency, and a shift to cleaner renewable energy sources. [11.9] *[very high confidence]*
- Providing access to reproductive health services and thus improving child and maternal health through increased birth spacing, while reducing population growth and consequent CAP emissions over time. [11.9] *[high confidence]*

11.1. Introduction

This chapter examines what is known about the effects of climate change on human health and, briefly, the more direct impacts of Climate-Altering Pollutants (CAPs) on health. We review diseases and other aspects of poor health that are sensitive to weather and climate. We examine the factors that cause populations and individuals to be particularly susceptible to ill-health due to variations in weather and climate, and describe steps that may be taken to reduce the impacts of climate change on human health. The chapter also includes a section on health "co-benefits." Co-benefits are positive effects on human health that arise from interventions to reduce emissions of CAPs.

Per IPCC guidelines, this is not a comprehensive, systematic review, but a scientific assessment based on the judgment of the authors. Literature was identified using a published protocol (Hosking and Campbell-Lendrum, 2012) and other approaches, including extensive consultation with technical experts in the field, through the multi-stage review process**.**

We begin with an outline of measures of human health, the major driving forces that act on health world-wide, recent trends in health status, and health projections for the remainder of this century.

11.1.1. Present State of Global Health

The Fourth Assessment Report pointed to dramatic improvement in life expectancy in most parts of the world in the 20th century, and this trend has continued through the first decade of the 21st century (Wang, 2012). Rapid progress in a few countries (especially China) has dominated global averages, but most countries have benefited from substantial reductions in mortality. There remain sizable and avoidable inequalities in life expectancy within- and between-nations according to education, income and ethnicity (Beaglehole and Bonita, 2008) and in some countries, official statistics are so patchy in quality and coverage that it is difficult to draw firm conclusions about health trends (Byass, 2010). At a regional level, inequalities in mortality have diminished, and convergence has been particularly marked amongst adults (Clark, 2011). Amongst children, mortality rates continue to fall, twice as quickly in the first decade of this century as in the 1990s (World Health Organization, 2011). The greatest decreases have occurred in urban areas and in wealthy parts of the world, and progress is uneven: more than 20 countries, mostly in sub-Saharan Africa, showed no reduction in child mortality between 1990 and 2006 (United Nations, 2010) (see Box 11-1).

_____ START BOX 11-1 HERE _____

Box 11-1. Climate Change and the Millennium Development Goals

The Millennium Development Goals (MDGs) were established in 2000, as a way of focusing attention on some of the most pressing international development goals. Progress toward many of the goals, which are to be accomplished by 2015--and any subsequent related development efforts--will be affected by climate change. For example, Goal 4 states that the world community should "reduce by two thirds, between 1990 and 2015, the under-five mortality rate."[1] Figure 11-1 shows the current trends in reduction in child mortality worldwide by cause and indicates how far they are expected to fall above the MDG reduction goal by 2015. Each color represents a different child-mortality "disease wedge" with different risk factors and interventions. It also indicates overall how much faster they together must decline if the MDG is even to be reached ten years late, i.e., by 2025. According to the scenarios reported by WG1, the greatest impacts of climate change will occur after this date (ie mid-century). There are three ways climate change interacts with these wedges:

1) Two of the major causes of child mortality, diarrhoeal diseases and malaria, are directly influenced by the changes in temperature and rainfall to be expected with climate change (11.5.2; 11.5.1), probably making their reduction more difficult as climate change proceeds.
2) Malnutrition/under-nutrition is a major contributor to all the child-mortality wedges represented here, and will be more difficult to control as climate change proceeds (11.6.1)
3) On a more positive note, improving combustion of solid-fuel in poor households will both help reduce one of the major wedges, acute respiratory illnesses, and mitigate climate change through reduction in CAPs, a co-benefit (11.9.1).

[FOOTNOTE 1: http://www.un.org/millenniumgoals/childhealth.shtml]

[INSERT FIGURE 11-1 HERE
Figure 11-1: Climate change acts against human development: to reach the Millennium Development Goal for child mortality, the reduction in climate-sensitive causes of death at an early age must accelerate. Projected child mortality, 2008-2030, including climate-sensitive causes. Sources: Mortality projections by cause from WHO. Population projections from UN DESA. Child mortality rates from IGME. (World Health Organization, 2008a; Interagency Group for Child Mortality Estimation, 2011; United Nations, Department of Economic and Social Affairs, Population Division, 2011).]

_____ END BOX 11-1 HERE _____

Health Adjusted Life Expectancy (HALE), a measure that incorporates premature mortality and years of healthy life lost due to disease and injury, has also improved substantially, world-wide, but with big differences between countries. For instance, in 2010 male HALE was 27.9 years in Haiti and 68.8 years in Japan (Salomon *et al.*, 2012). (World Health Organization, 2009a; World Health Organization, 2010; World Health Organization, 2011a)Not all indicators are positive. For instance, child under-nutrition, implicated in about a third of all deaths under 5 years, increased in some countries between 2005 and 2008, and about 180 million children world-wide are stunted (short for their age) as a consequence (World Health Organization, 2010).

For specific causes of death, the patterns differ widely by region. The dramatic decline in cardiovascular disease in high-income countries is not seen in parts of the world that are developing rapidly, such as India and China. In those countries, the numbers of deaths from heart disease and stroke are increasing for two reasons; ageing populations and prevalent risk factors such as high blood pressure and cigarette smoking (Samb *et al.*, 2010). Cancer, diabetes, overweight, obesity, and mental disorders such as depression are also reported more commonly than previously in many low and middle income countries (Finucane *et al.*, 2011).

Most researchers anticipate mortality rates will continue to fall world-wide, and WHO estimates the total burden of disease (measured in DisabilityAdjusted Life Years per capita) will be cut by as much as 30% in 2030, compared with 2004 (World Health Organization, 2008b; World Health Organization, 2008c). These projections assume that economic and social development continue without interruption, particularly among poor populations, and as

already noted, the global figures are dominated by trends in a few large countries (China and India in particular) (Mathers and Loncar, 2006). The underlying causes of poor health are expected to change substantially, with much greater prominence of chronic diseases and injury, largely due to changes in population structure. On its "baseline development" scenario, WHO projects the top three causes of burden of disease in 2030, world-wide, to be depression, ischemic heart disease and road traffic accidents (World Health Organization, 2008c).

11.1.2. Developments since AR4

The relevant literature has grown considerably since publication of AR4. For instance, the annual number of MEDLINE citations on climate change and health doubled between 2007 and 2009 (Hosking and Campbell-Lendrum, 2012). We ran the same search protocol once more in January 2013 and found the number of citations per annum continued to grow after 2009, but at a slower rate. In addition, there are many reviews, reports and international assessments that do not appear in listings such as MEDLINE but include important information nevertheless, for instance, the World Development Report 2010 (The World Bank, 2010), the Climate Vulnerability 2010 report (DARA, 2010), and the 2011 UN Habitat report on cities and climate change (United Nations Human Settlements Programme, 2011). Many of these publications were reviews and commentaries, and a smaller number of quantitative studies linking climate change and health. One review of the scientific literature from 2008 to 2011 identified 40 studies of this latter kind, most focused on high-income countries (Hosking and Campbell-Lendrum, 2012).

Since the AR4, there have been improvements in the methods applied to investigate climate change and health. They include more sophisticated modeling of possible future impacts (for example, work linking climate change, food security, and health outcomes) (Nelson *et al*., 2010) and new methods to model the effects of heat on work capacity and labor productivity (Kjellstrom *et al*., 2009b). Other developments include coupling of high-quality, longitudinal mortality data sets with down-scaled meteorological data, in low-income settings (for instance, through the INDEPTH Network) (see Box 11-2).

_____ START BOX 11-2 HERE _____

Box 11-2. Weather, Climate and Health – a Long-Term Observational Study in African and Asian Populations

Given the dearth of scientific evidence of the relationship between weather/climate and health in low- and middle-income countries, we report on a collaborative study from sub-Saharan Africa and Asia. The INDEPTH Network currently has 43 members in 20 countries in Africa, Asia and Oceania. Using standardized health and demographic surveillance systems members have collected information on births, migration and deaths by cause over an average of 20 years.[2] Currently, there are about 3.4 million people under surveillance.

To study long-term relationships between weather and health, the authors collected information on all deaths occurring in 11 INDEPTH populations between 1 January 2000 and 31 December 2009 contributing about 10 million person-years of observation over 10 years (Diboulo *et al*., 2012). Time dependent methods were used to relate meteorological data to health outcomes. Seasonality in mortality varies between age groups, and there are differences in susceptibility to weather related factors by gender. In the elderly population deaths related to dust storms and heat have been more pronounced compared with other ages. For example, in Nounain Burkina Faso, the relative risk of dying for the elderly above 60 years is associated with the temperature on the day preceding the death, as shown in Figure 11-2.

[INSERT FIGURE 11-2 HERE
Figure 11-2: Relationship between the risk of dying and average temperature on the preceding day, persons aged over 60 years, Nouna, Burkina Faso. Y-axis: log(RR), X-axis: Temp in °C, lagged by one day. Dotted lines show 95% confidence limits. Source: Diboulo et al, 2012.]

[FOOTNOTE 2: http://www.indepth-network.org]

_____ END BOX 11-2 HERE _____

Since AR4, studies of the ways in which responses to climate change may affect health, so-called "co-benefits," have multiplied (Haines *et al*., 2009). There has been growing interest also in effects of greenhouse emissions other than climate change. A prime example is ocean acidification (Doney *et al*., 2008).

Much has been written on links between climate, socioeconomic conditions and health, for example related to occupational heat exposure (Kjellstrom *et al*., 2009b) and malaria (e.g. (Gething *et al*., 2010; Béguin *et al*., 2011)) There is also growing appreciation of the social upheaval and damage to population health that may arise from the interaction of large-scale food insecurity, population dislocation, and conflict (Princeton Study, 2013).

11.1.3. Non-Climate Health Effects of Climate-Altering Pollutants (CAPs)

CAPs affect health in other ways than through climate change, just as CO_2 creates non-climate effects such as ocean acidification. The effects of rising CO_2 levels on calcifying marine species are well documented and the risks for coral reefs are now more closely defined than they were at the time of the AR4. There are potentially implications for human health such as malnutrition in coastal populations that depend on local fish stocks, but, so far, links between health and ocean acidification have not been closely studied (Kite-Powell *et al*., 2008). CAPs such as black carbon and tropospheric ozone are also constituents of air pollution, and have major effects on human health. See section 11.5.3 and Box 11-4.

11.2. How Climate Affects Health

There are three basic pathways by which climate change affects health as illustrated in Figure 11-3. These provide the organization for the chapter.

- **Direct impacts**, which relate primarily to heat, weather extremes, and floods that directly impact human health and safety. [11.4]
- **Effects mediated through natural systems,** for example, disease vectors, water-borne diseases, and air pollution. [11.5]
- **Effects heavily mediated by human systems**, for example, occupational impacts, malnutrition, refugees, and mental stress. [11.6]

[INSERT FIGURE 11-3 HERE
Figure 11-3: Ways in which climate, climate variability and climate change may influence human health.
Source: E. Garcia (2011).]

To a considerable extent, the health impacts in each of these categories could be greatly ameliorated by efforts to improve infrastructure, public health services, disaster management, and poverty alleviation, although at considerable cost and effort. There is another category of impacts, however, that would be much more difficult to deal with:

- **Lower probability extreme climate regimes** beyond 2050 for which there seems no reasonable adaptation options. [11.8]

Before exploring what is known in each of these areas, however, we summarize what is known about vulnerability that affects all these types of impact.

11.3. Vulnerability to Disease and Injury due to Climate Variability and Climate Change

In the IPCC assessments, vulnerability is defined as the propensity or predisposition to be adversely affected (Chapter 19). In this section, we consider causes of vulnerability to ill-health associated with climate change and climate variability, including internal characteristics of the individuals affected, properties of the population in which these individuals live, and factors in the physical environment.

The background climate-related disease rate of a population is the best single indicator of the vulnerability to climate change - doubling of risk of disease in a low disease population has much less absolute impact than doubling of the disease when the background rate is high.

We have divided the causes of vulnerability into sections for convenience. In practice, these factors combine, often in complex and place-specific manner. There are some factors (such as education, income, health status and responsiveness of government) that act as generic causes of vulnerability. Low levels of parental education, for example, are consistently associated with higher child mortality in times of stress, whether it is military conflict, famine, or other natural disasters. The quality of governance – how decisions are made and put into practice – affects a community's response to threats of all kinds (Bowen et al, 2012). But the precise causes of vulnerability, and therefore the most relevant coping capacities, vary greatly from one setting to another. Vulnerability to heat, for example, varies spatially: the factors that are important in rural areas differ from those that put people at risk in cities (Reid *et al*., 2009). In a similar vein, severe drought in Australia has been linked to psychological distress and to food insecurity – but only for those residing in rural and remote areas. (Berry et al, 2010). The link between high ambient temperatures and increased incidence of salmonella food poisoning has been demonstrated in many places (e.g. (Zhang *et al*., 2010)), but the lag varies from one country to another, suggesting that the mechanisms differ (deficiencies in food storage may be the critical link in some places, food handling problems may be most important elsewhere) (Kovats *et al*., 2004).

The 2010 World Development Report concluded that all developing regions are vulnerable to economic and social damage resulting from climate change – but for different reasons (The World Bank, 2010). The critical factors for Sub-Saharan Africa, for example, are the current climate stresses (in particular, droughts and floods) that are projected to worsen with climate change, sparse infrastructure and high dependence on natural resources. Asia and the Pacific, on the other hand, are distinguished by the very large number of people living in low-lying areas prone to flooding (this includes roughly half the population of Vietnam, and nearly all of Bangladesh).

11.3.1. Geographic Causes of Vulnerability

Location has an important influence on the potential for losses caused by climate change (Samson *et al*., 2011). Those living in inland cities at mid- and low latitudes, where present-day temperatures are frequently close to tolerable maxima, will be more severely affected by further warming than people living at high latitudes (Kjellstrom *et al*., 2013). The inhabitants of low-lying coral atolls are exquisitely sensitive to flooding, contamination of fresh water reservoirs due to sea level rise, and salination of soil, all of which may have important effects on health (Nunn, 2009). Rural populations that rely on subsistence farming in low rainfall areas are at high risk of under-nutrition and water-related diseases in future drought, although this vulnerability may be modified strongly by local factors, such as access to markets and irrigation facilities (Acosta-Michlik *et al*., 2008). In high-income countries, location remains an important measure of susceptibility to the adverse effects of climate change. For example, living within 100- and 500-year flood zones, or within 5 km of coasts subject to sea level rise have been proposed, in the United States, as indicators of vulnerability to flooding (Acosta-Michlik *et al*., 2008; English *et al*., 2009). Living in rural and remote areas confers increased health risk because of poor access to services and generally higher levels of social and economic disadvantage. (Smith, 2008) Populations that are close to the present limits of transmission of vector-borne diseases are most vulnerable to changes in the range of transmission due to rising temperatures and altered patterns of rainfall (Zhou *et al*., 2008).

11.3.2. Current Health Status

Climate extremes may promote the transmission of certain infectious diseases and the vulnerability of populations to these diseases will depend on the baseline levels of pathogen and vector. In the United States, as one example, arboviral diseases such as dengue and the encephalitides are rarely seen after flooding, compared with the experience in other parts of the Americas. The explanation lies in the scarcity of dengue and other viruses circulating in the population, pre-flooding (Keim, 2008). Schistosomiasis was present in parts of Portugal in the 1950s. However, disease control efforts have eliminated the microbe from local snail populations so that although there is a competent vector and climate projections indicate that both parasite survival and vector survival will be favoured by rising temperatures, the risk of schistosomiasis returning to Portugal is low (Casimiro *et al.*, 2006). On the other hand, the high prevalence of HIV infection in many populations in Sub-Saharan Africa multiplies the health risks of prolonged drought, which may lead to migration, family disruption, deepening poverty, and increased exposure to unsafe sex.

11.3.3. Age and Gender

Children, young people, and the elderly are at increased risk of climate-related injury and illness (Perera, 2008). For example, illness due to malaria, diarrhea, and malnutrition is presently concentrated amongst children, for reasons of physiological susceptibility. In principle, children are expected to be more vulnerable to heat-related illnesses, due to their small body mass to surface area ratio, but evidence of excess heat-related mortality in this age group is mixed. In California, a study of summer mortality records for 1999-2003 reported a stronger association of heat and mortality among infants (aged less than 1 year) and those aged 65 years and over than other age groups (Basu and Ostro, 2008). Other studies have sought, but not detected, such an association (Kovats and Hajat, 2008). Malaria parasites in the blood are more plentiful and mortality from malaria is more common in childhood (from about 6 months to 3 years) due to less well-developed immune responses to infection with the plasmodium (Michon *et al.*, 2007). Children dehydrate more rapidly than adults when affected by diarrhoeal diseases, and case-fatality rates are correspondingly higher. In some circumstances, children may be protected from climate-related diseases. For instance, maternal antibodies lower the risk of dengue fever in children in the first year of life. Children are generally at greater risk when food supplies are restricted. Households with children tend to have lower than average incomes, and childhood is a particularly sensitive period for health and development (Cook and Frank, 2008). Young people are at risk of mental health-related climate change impacts because, unlike for physical illness, mental illness peaks in youth.

Older people are at greater risk from storms, floods, heat-waves and other extreme events, in part because they tend to be less mobile than younger adults and so find it more difficult to avoid hazardous situations and also because they are more likely to live alone, in some cultures. Older people are also more likely to suffer from health conditions that limit the body's ability to respond to stressful events. Chronic diseases such as diabetes and ischemic heart disease, for example, magnify the risk of death or severe illness associated with high ambient temperatures (Basu and Ostro, 2008; Sokolnicki *et al.*, 2009). People over 65 years are also more strongly affected by air pollution due to ozone and other photochemical oxidants (Medina-Ramon *et al.*, 2006).

Vulnerability is associated with gender but the relationship is complex (World Health Organization, 2011b). In the United States, it is reported that males are at greater risk of death following flooding, perhaps because in this setting they are more commonly exposed to risk (e.g. many of the flood drownings in the US are motor-vehicle related, and on average, in this country, males drive more than females do) (Jonkman and Kelman, 2005). A study of the health effects of flooding in Hunan province, China, also found an excess of flood deaths among males, often related to rural farming (Abuaku *et al.*, 2009). In Canada's Inuit population males are exposed to dangers associated with insecure sea ice, while females may be more vulnerable to the effects of diminished food supplies (Pearce *et al.*, 2011). In the Paris 2003 heatwave, females were more affected than males in every age group except those aged 25-64. In this instance, the male dominance in the working age group may be related to differential exposures to heat in occupational settings. In Bangladesh, females are more affected than males by a range of climate hazards, at least in part because a greater proportion suffers from poverty and poor nutrition, and women are more frequently exposed to water-logged environments (Neelormi *et al.*, 2009). There may also be physiological differences in resilience.

After controlling for differences in age and co-morbidities, it appears that females are more strongly affected than males by high temperatures (Yu *et al.*, 2010) and ozone air pollution (Medina-Ramon and Schwartz, 2008). There are signs also that the effect of food insecurity on growth and development in childhood may be more damaging for girls than boys (Cook and Frank, 2008).

Pregnancy is a period of increased vulnerability to a wide range of environmental hazards, including extreme heat (Strand *et al.*, 2012) and infectious diseases such as malaria, foodborne infections and influenza (Jamieson *et al.*, 2006)(van Kerhove et al, 2011).

11.3.4. Socioeconomic Status

Socioeconomic status typically is measured by educational attainment, occupational prestige and personal income. At a national level, the poorest countries are most susceptible to damage caused by climate change, including health effects. Likewise, individuals and households most vulnerable to climate hazards are those with relatively low socioeconomic status. A review of global trends in tropical cyclones found that mortality risk depended on storm intensity, effective governance, and levels of poverty (Peduzzi *et al.*, 2012). A study of the impacts of flooding in Bangladesh found that household risk reduced with increases in both average income and number of income sources. Poorer households were not only more severely affected by flooding, but they took preventive action less often, and received assistance after flooding less frequently than did more affluent households. This was explained partly by financial obstacles to relocation and other coping strategies, but there were differences also in knowledge of hazards and in beliefs about the preventability of flooding (Brouwer *et al.*, 2007).

Occupation is also directly related to vulnerability to climate variability and extremes. For instance, outdoor occupations, which tend to have low socio-economic status, have been linked with disease and injury caused by flooding in China (Abuaku *et al.*, 2009) and heat-waves in the United States (Centers for Disease Control and Prevention, 2008). Tawatsupa et al (2010) report differences in Thailand in the impacts of heat in the workplace in relation to socio-economic status. High socioeconomic status is not always protective: Singapore is one of the wealthiest countries in Asia, but in the 2000s experienced a resurgence of dengue fever, despite a considerable investment in vector control (Egger et al, 2008). In Brisbane, Australia, heat-wave mortality was related to age and gender, but not to small area measures of social disadvantage (Yu *et al.*, 2010). This null finding, contrary to what has been observed elsewhere with individual-level measures of SES, (Medina-Ramon *et al.*, 2006) may be due to the much greater variability in housing quality in Australia within neighborhoods than exists between neighborhoods, or the relatively flat social gradient in access to protective factors such as air conditioning and private transport.

In many countries, race and ethnicity are powerful markers of health status and social disadvantage. Black Americans have been reported to be more vulnerable to heat-related deaths than other racial groups in the United States (Basu and Ostro, 2008). This may be due to a higher prevalence of chronic conditions such as over-weight and diabetes, (Lutsey *et al.*, 2010) to financial circumstances (for instance, lower incomes may restrict access to air conditioning during heat-waves), (Ostro *et al.*, 2010) or to community-level characteristics (such as higher local crime rates or disrupted social networks). Indigenous peoples who depend heavily on local resources, and live in parts of the world where climates are changing quickly, are generally at greater risk of economic losses and poor health. Studies of the Inuit people, for example, show that rapid warming of the Canadian Arctic is jeopardizing hunting and many other day-to-day activities, with implications for livelihoods and well-being (Ford, 2009). Climate change in the North-West of Alaska led to increased vulnerability to accidents, diseases, mental stress, and food insecurity. Increase in temperature in the traditional ice cellars used for storage of fish and meat of sea mammals increases risks of food-borne and gastrointestinal diseases (Brubaker, M., Berner, J., Chavan, R., Warren,J., 2011). In Australia, indigenous peoples experience higher rates of diarrheal diseases and other climate-sensitive conditions than the remainder of the national population and their general health status is poorer, which places them at additional risk of climate stressors such as heat-waves (Petheram *et al.*, 2010). They also experience greatly elevated rates of mental illness, suicide (Hunter, 2009) and related health behaviours, and these create substantial underlying vulnerability to climate change (Berry *et al.*, 2010a)(Berry, 2009).

11.3.5. Public Health and Other Infrastructure

The physical environments around where people live and work can influence the health risks due to climate variability and climate change. In Cuba, a country with a well-developed public health system, dengue fever has been a persistent problem in the larger cities, due in part to the lack of a constant supply of drinking water in many neighbourhoods (leading to people storing water in containers that are suitable breeding sites for the disease vector, *A. aegypti*) (Bulto *et al.*, 2006). A study of the city of Phoenix, in the US, found the number of heat distress calls during heat waves was higher in areas affected by the urban heat island effect (which was measured by the proportion of impervious surfaces and minimum night time temperatures) (Uejio *et al.*, 2011).

11.3.6. Projections for Vulnerability

Population growth may be one of the strongest influences on vulnerability to the health effects of climate change. Increasing numbers of people, in locations that are already resource-poor and are affected by climate risks, will magnify harmful impacts. Most of the projected growth in populations will occur in large, low latitude hot countries in which a high proportion of the workforce is deployed outdoors with little protection from heat. About 150 million people currently live in cities affected by chronic water shortages (< 100 L per person per day of sustainable freshwater flows) and in 50 years, unless there are rapid improvements in urban environments, demographic growth will push the number affected by chronic water shortages to around a billion (McDonald *et al.*, 2011). Under a "business as usual" scenario, the OECD projects that about 1.4 billion people will be without access to basic sanitation in 2050 (OECD, 2012). The age structure of the population also has implications for vulnerability. The proportion aged over 60, world-wide, is projected to increase from about 10% presently to about 32% by the end of the century (Lutz *et al.*, 2008). Overweight and obesity, associated with relatively poor heat tolerance, are becoming more common in most countries, and this trend is expected to continue (Finucane *et al.*, 2011).

Future trends in social and economic development are critically important to vulnerability. For instance, countries with a higher Human Development Index (HDI) (a composite of life expectancy, education and literacy and GDP per capita) are less affected by the floods, droughts and cyclones that take place (Patt *et al.*, 2010). Therefore policies that boost health, education and economic development should reduce future vulnerability. Overall, there have been substantial improvements in the HDI, but this has been accompanied by increasing inequalities between and within countries, and has come at the cost of high consumption of environmental resources (UNDP, 2011). The relation between national wealth and health is roughly log linear, suggesting that an extra dollar buys more health gain in low-income countries than in medium and high income settings. It is notable also that the protective effects of national wealth are related to the severity of climate extremes. Peduzzi (2012) found "that poverty levels are less significant when facing very intense tropical cyclones, whereas at the lower intensities only the poorest suffer heavy losses."

11.4. Direct Impacts of Climate Meteorological Changes on Health

11.4.1. Heat and Cold Extremes

Although there is strong evidence for the effects of variation in weather and season on a range of health outcomes, assessment of health impacts of observed climate change in the last few decades is challenging. Over the multi-decadal time scales that are necessary to measure climate change, the constellation of factors that influence disease rates is strongly affected by many other social and environmental factors. This means that robust studies require not only long time series of data on climate and disease rates, but also information on all other established or potential causative factors, coupled with statistical analysis to apportion changes in health states to the various contributing factors. To complicate matters further, wherever risks are identified, health agencies are mandated to intervene immediately, confounding long-term analyses. Finally, there is no clear consensus on appropriate methods and standards for studies correlating long-term time trends in environmental variables and health outcomes. Such studies are therefore relatively rare, and seldom conclusive.

Since AR4, there is stronger evidence both for increases in some meteorological exposures that are hazardous to human health, and of attribution of these changes to anthropogenic influences. The IPCC Special Report on Extreme Events SREX [to be updated with data from AR5 WG1] concludes that it is very likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale.

In some cases, the connection between meteorological hazards and health impacts is sufficiently direct to draw strong inferences about cause and effect (Sauerborn and Ebi, 2012). Most notably, the association between unusually hot days (defined as departures from average daily maximum temperatures for a specified location and date over 20 or 30 year baseline period) and increases in mortality is very robust (see studies reviewed in section 11.2.2 above). The observed *very likely* increase in daily maximum temperatures is therefore *likely* to have caused an increase in the number of heat-related deaths in mid-latitude populations. The decrease in minimum temperatures may have contributed to a decline in deaths associated with cold spells in the same populations, but there is no strong evidence in the literature so far. Moreover, the influence of seasonal factors other than temperature on winter mortality suggests that heat impacts on health may outweigh the benefits of fewer cold days (Kinney *et al.*, 2012; Ebi and Mills, 2013). Quantification globally, remains highly uncertain, as there are few studies of the large developing country populations in the tropics, and those which do exist point to effects of heat, but not cold, on mortality (Hajat *et al.*, 2010). There is also significant uncertainty over the degree of physiological, social or technological adaptation to increasing heat over long time periods. For other extreme events and weather disasters (such as floods or drought), there is no good evidence of a climate change signal (IPCC, 2012).

11.4.1.1.Mechanisms

It is physiologically plausible that circulatory diseases are more common at high temperatures; for instance, displacement of blood to the skin surface may lead to circulatory collapse. In this regard, indoor thermal conditions are important, including ventilation, humidity, radiation from walls or ceiling and the presence or absence of air-conditioning, but these variables are seldom well-measured in epidemiological studies (Anderson *et al.*, 2012). Biological mechanisms are less evident for other causes of death that have been related to weather. For instance, there is an association of ambient temperature with suicide (Page *et al.*, 2007; Likhvar *et al.*, 2011; Kim *et al.*, 2011).

Some investigators have reported that mortality increases more during heat waves than would be anticipated solely on the basis of physiologic tolerance to temperature (D'Ippoliti *et al.*, 2010; Anderson and Bell, 2011), although the added effect is relatively small in some series, and most evident with prolonged heat waves. (Gasparrini and Armstrong, 2011) Some studies have shown larger effects of heat and heat waves earlier in the hot season (Anderson and Bell, 2011; Rocklov *et al.*, 2011). This may be testament to the importance of acclimatisation and adaptive measures, or may result from a large group in the population that is genuinely susceptible to heat early in the season (Rocklov *et al.*, 2009; Rocklov *et al.*, 2011).

The extreme heat wave in Europe in 2003 led to numerous epidemiological studies. The reports from France (Fouillet *et al.*, 2008)concluded that a very large proportion of the extra deaths occurred in elderly people (80% above age 75). However, heat wave-related mortality in younger ages was also substantial (approximately 3,000 deaths). Questions were raised at the time as to why this event had such a devastating effect (Kosatsky, 2005). It is still not clear, but one contributing factor may have been the relatively mild influenza season the year before. Recent studies have found that when the previous year's winter mortality is low, the effect of summer heat is increased (Ha *et al.*, 2011). This relationship between risk factors in winter and summer time may complicate the attribution of heat and cold effects (e.g. with climate change), given their inter-dependence; milder winters may leave a higher proportion of vulnerable people, and predispose to a stronger subsequent summer heat effect (Stafoggia *et al.*, 2009).

Most studies of heat have been in high-income countries, but there has been work recently in low- and middle-income countries, suggesting heterogeneity in vulnerability by age groups and socio-economic factors similar to that seen in higher-income settings (McMichael *et al.*, 2008; Bell *et al.*, 2008b; Pudpong and Hajat, 2011).

Studies of temperature-related morbidity, most commonly based on hospital admission or emergency presentations, find increases particularly in cardio-vascular, respiratory and kidney diseases. (Hansen *et al*., 2008; Lin and Chan, 2009; Knowlton *et al*., 2009). Rapid changes in temperature may upset the balance between humans and parasites. It has been proposed that the speed with which organisms adapt to changes in temperatures is broadly speaking a function of mass, and in support of this proposition, laboratory studies have shown that microbes respond more quickly to a highly variable climate than do their multi-cellular hosts (Raffel *et al*., 2012).

Health risks during heat extremes are greater in people carrying out physical activity. The intra-body surplus heat created by physical activity causes particular vulnerability to heat effects in these population groups. This has importance for recreational physical activity outdoors and it is of special relevance to analysis of the impacts of climate change on occupational health (see separate section below) (Ebi and Mills, 2013). Since the association between unusually hot days and increases in mortality is so well documented, it is possible to conclude that an observed increase in daily maximum temperatures is *likely* to have caused an increase in the number of heat-related deaths. The decrease in minimum temperatures may have contributed to a decline in deaths associated with cold spells in the same populations. There are very few studies of the large developing country populations in the tropics, and those which do exist point to effects of heat, but not cold, on mortality (Hajat *et al*., 2010). There is also significant uncertainty over the degree of physiological, social or technological adaptation to increasing heat over long time periods.

11.4.1.2.Near-Future Impacts

Under predicted climate change scenarios, it is likely heat waves will increase in frequency and intensity and worsen heat-related exposures, although acclimatization and improvements in energy efficiency may mitigate some of these effects (Wilkinson *et al*., 2007a; Wilkinson *et al*., 2007b; Bi and Parton, 2008; Hanna *et al*., 2011; Maloney and Forbes, 2011). In Australia, the number of "dangerously hot" days, when core body temperatures may increase by ≥ 2ºC and outdoor activity is hazardous, is forecast to rise from the current 4 to 6 days per year to 33-45 days per year by 2070 for non-acclimatized people. Among acclimatized people, an increase from 1-5 days per year to 5-14 days per year is expected (Hanna *et al*., 2011).

For reasons given above, it is not clear whether winter mortality will decrease in a warmer, but more variable climate (Kinney *et al*., 2012; Ebi and Mills, 2013). Overall, the increase in heat-related mortality is projected to outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations (Wilkinson *et al*., 2007b). A study of three Quebec cities projected an increase in summer mortality that clearly outweighed a small reduction in autumn deaths, and only slight variations in winter and spring (Doyon *et al*., 2008). Another study, using years of life lost as the outcome, and located in Brisbane, Australia, found the gains associated with fewer cold days were outweighed by the effects of more hot days when warming exceeded 2ºC. (Huang *et al*., 2012). The same trend is reported for New York City: by the 2050s, premature mortality due to heat is projected to increase by 70% (Knowlton *et al*., 2007). It is not certain how rapidly populations may adjust to increased heat. In New York, it was estimated that acclimatisation may reduce the impact of added summer heat by roughly a quarter (Knowlton *et al*., 2007).

11.4.2. Floods

In the IPCC Fourth Assessment Report, floods were reported to be the most frequent natural weather disaster. This is still true; in 2010, the ten most important disasters, judged by the number of people affected, included six floods and these floods accounted for more than 90% of the total number of victims, i.e., 175 million people (Guha-Sapir *et al*., 2011). Most of the losses occurred in mid- to low-income countries such as China, Pakistan (Dar *et al*., 2011), Thailand, Cambodia, India, and Colombia. For instance, in 2007 flooding along the southern coast of Mozambique affected 285,000 people, caused 140,000 to be displaced from their homes, and led to 29 deaths (World Bank, 2011). However, as exemplified by severe, damaging floods in Australia in 2010 and in the north-east of the United States in 2012, developed countries are not immune. (Guha-Sapir *et al*., 2011; Powell, 2012).

Mechanisms

The direct impacts of storms and floods include drowning, injuries, hypothermia and infectious diseases, whereas indirect health effects result from damage to infrastructure and water supplies, displacement of people, and disruption to people's lives (Jonkman and Kelman, 2005). Over the last 10 years, floods in Europe have killed more than 1,000 people and affected over 3.4 million. Worldwide, it is estimated that two thirds of flood deaths are due to drowning, and 70% of flood-related deaths are male (Jonkman and Kelman, 2005).

The attribution of deaths to flood events has been found to be complex with immediate traumatic deaths being most easily recorded (WHO/HPA, 2012). There is some uncertainty as to whether flood events are associated with a longer-term effect on mortality in the flooded population (Milojevic *et al*., 2011). A study in rural Bangladesh found no effect on flooding on subsequent diarrhoeal disease, but a small increase (RR 1.25) in acute respiratory infections (Milojevic *et al*., 2012). Another report on Bangladesh found no evidence of increased risk of mortality or diarrhea during 3 years after flooding (Milojevic *et al*., 2012).

Flood-related injuries have been caused when people are evacuating from flood waters, attempting to save family or valuables, or during the clean-up process (Schnitzler *et al*., 2007; Jakubicka *et al*., 2010). Drinking water can become contaminated by bacteria, sewage, agricultural waste or chemicals (CDC, 2011). Infectious diseases and vector mosquitos for malaria or dengue fever may also be affected by floods (Kouadio *et al*., 2012). In many countries, heavy rainfall and flooding have led to outbreaks of leptospirosis (caused by contact with bacteria of the genus *Leptospira*, an organism which circulates in a wide variety of animal hosts, including rats) (Lau *et al*., 2010). Flooding and storms may have profound effects on peoples' mental health (Neria, 2012). A study of the aftermath of the 2007 England and Wales floods found that the prevalence of mental health symptoms (including psychological distress, anxiety and depression) was two to five times higher among individuals who reported flood water in the home compared to individuals who did not (Paranjothy *et al*., 2011). In Taiwan, a survey conducted 3 months after Typhoon Markot found the prevalence of Post Traumatic Stress Disorder was 25.8% among 271 evacuated school children (Yen *et al*., 2011).

We found no studies of near-future impacts of storms and flooding published since AR4.

11.4.3. Ultraviolet Radiation

Ambient UV levels and maximum summertime day temperatures are related to the prevalence of non-melanoma skin cancers. In one study in the United States, the number of cases of squamous cell carcinoma was 5.5% higher for every 1°C increment in average temperatures, and basal cell carcinoma was 2.9% more common with every 1° C increase. These values correspond to an increase in the effective UV dose by 2% for each 1°C (van der Leun *et al*., 2008). Higher temperatures in the northern countries and countries with temperate climates may result in an increase in the time which people spend outdoors and, thus in additional UV-induced-adverse effects. Notably, however, skin cancer rates are rising already in many countries, for other reasons, such as changes in travel and recreation.

11.5. Ecosystem-Mediated Impacts of Climate Change on Health Outcomes

11.5.1. Vector-Borne and Other Infectious Diseases

Vector-borne diseases (VBDs) refer most commonly to infections transmitted by the bite of infected insects such as mosquitoes or ticks. These are perhaps the most well-studied of the diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors (Bangs *et al*., 2006; Bi *et al*., 2007; Halide and Ridd, 2008; Wu *et al*., 2009). Table 11-1 summarizes what is known.

[INSERT TABLE 11-1 HERE
Table 11-1: Vector-borne diseases.]

11.5.1.1. Malaria

Malaria is mainly caused by four distinct species of plasmodium parasite (Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae, Plasmodium ovale), transmitted between individuals by Anopheline mosquitoes. In 2010 there were an estimated 216 million episodes of malaria world-wide, causing 655,000 deaths, mostly of children under 5 years in the African Region (WHO, 2011). World-wide, there have been significant advances made in malaria control in the last 20 years (Feachem, 2011), but the disease persists and is a challenge, particularly, in Africa. For example, large outbreaks have occurred in highland regions in East Africa, and these may have been promoted, at least in part, by rising temperatures locally (Chaves and Koenraadt, 2010).

The influence of temperature on malaria development appears to be non-linear, and is vector-specific (Alonso *et al.*, 2011). Daily minimum temperature fluctuation acts to speed up parasite development, whereas variations around the maximum temperature tend to slow processes down (Paaijmans *et al.*, 2010). Analysis of environmental factors associated with the malaria vectors *Anopheles gambiae* and *Anopheles funestus* in Kenya found that abundance, distribution and disease transmission are affected in different ways by precipitation and temperature (Kelly-Hope *et al.*, 2009). There are lag-times according to the life cycle of the vector and the parasite: a study in one county of central eastern China reported that malaria incidence was related to maximum temperature and average humidity one month prior to identification of the case (Zhang *et al.*, 2012).

More work has been done since AR4 to elucidate the role of local warming on malaria transmission in the East African highlands, but this is hampered by the lack of time series data on factors such as levels of drug resistance and intensity of vector control programmes. Earlier research had failed to pick out a clear increase in temperatures accompanying increases in malaria transmission, but new studies with aggregated meteorological data over longer time periods have confirmed increasing temperatures since the 1950s (Omumbo *et al.*, 2011; Stern *et al.*, 2011). The strongly non-linear response to temperature means that even modest warming may drive large increases in transmission of malaria, if conditions are otherwise suitable (Pascual *et al.*, 2006; Alonso *et al.*, 2011). A detailed review (Chaves and Koenraadt, 2010) concluded that decadal temperature changes have played a role in changing malaria incidence in East Africa. But malaria is very sensitive also to socioeconomic factors and health interventions, and the generally more conducive climate conditions have been offset by more effective disease control activities. The incidence of malaria has reduced over much of East Africa (Stern *et al.*, 2011) although increased variability in disease rates has been observed in some high altitude areas (Chaves et al, 2012).

At the global level, economic development and control interventions have dominated changes in the extent and endemicity of malaria over the last 100 years (Gething *et al.*, 2010). Although modest warming is likely to have facilitated malaria transmission, the proportion of the world's population affected by the disease has been reduced, largely due to control of *P. vivax* malaria in moderate climates with low transmission intensity.

11.5.1.2. Dengue Fever

Dengue is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years. Estimates for the population at risk range from 30% to 54.7% of the world's population (2.05–3.74 billion). Three quarters of the people exposed to dengue are in the Asia-Pacific region. The disease is associated with climate on spatial (Beebe *et al.*, 2009; Russell *et al.*, 2009; Li *et al.*, 2011), temporal (Hii *et al.*, 2009; Hsieh and Chen, 2009; Herrera-Martinez and Rodriguez-Morales, 2010; Earnest *et al.*, 2011; Gharbi *et al.*, 2011; Pham *et al.*, 2011; Descloux *et al.*, 2012) and spatiotemporal (Chowell *et al.*, 2008; Chowell *et al.*, 2011; Lai, 2011) scales.

The principal vectors for dengue, *Aedes aegypti* and *Aedes albopictus* are climate-sensitive. Over the last two decades, climate conditions have become more suitable for *albopictus* in some areas (eg over central northwestern

Europe) but less suitable elsewhere (eg over southern Spain) (Caminade *et al*., 2012) Distribution of *Aedes albopictus* in northwestern China is highly correlated with annual temperature and precipitation (Wu *et al*., 2011). Temperature, humidity and rainfall are positively associated with dengue incidence in Guangzhou, China, and wind velocity is inversely associated with rates of the disease. (Lu and Lin, 2009; Li *et al*., 2011)**.** A study in Dhaka, urban Bangladesh reported increased rates of admissions to hospital due to dengue with both high and low river levels (Hashizume and Dewan, 2012). In some circumstances, it is apparent that heavy precipitation favors the spread of dengue fever, but drought can also be a cause if households store water in containers that provide suitable mosquito breeding sites (Beebe *et al*., 2009; Padmanabha *et al*., 2010).

_____ START BOX 11-3 HERE _____

Box 11-3. Case Study: Dengue Fever

Dengue Fever (DF) and its haemorrhagic manifestations are caused by four antigenically distinct serotypes (1 to 4) belonging to the Flaviviridae family. Each year within the "dengue belt" (between 35ºN and 35ºS latitude) there occur about 50-100 million cases of Dengue Fever and 500,000 cases of Dengue Haemorrhagic Fever (DHF) and Dengue Shock Syndrome (DSS) (Chadee *et al*., 2007). Prior to 2006, no consistent patterns had been reported in the seasonal distribution of DF and *Ae. aegypti* adult populations within the Americas. However, seasonality in dengue transmission is well known in South East Asia, with transmission occurring mostly during the wettest months of the year (Gubler and Kuno, 1997; Chadee *et al*., 2007).

Figure 11-4 shows most DF cases in Trinidad (80%) were recorded during the wet season when the *Aedes aegypti* mosquito population density was four to nine times higher than the dengue transmission threshold (Macdonald, 1956). This led to a control programme that concentrated on reducing the mosquito population before the onset of the rains, by application of insecticides (temephos) into the water drums that serve as primary breeding sites of *Ae. aegypti* in the Caribbean. The one-off treatment effectively controlled the mosquito populations for almost 12 weeks after which the numbers reverted to levels observed in the untreated control areas.

[INSERT FIGURE 11-4 HERE
Figure 11-4: Rainfall, temperature, Breteau index (number of water containers with *A. aegypti* larvae per 100 houses), and dengue cases, Trinidad (2002-2004). Source: Chadee *et al*. (2007).]

Recent climate change scenarios for the period 2071-2100 project altered dynamic circulation patterns in both dry and wet seasons, therefore changing the intensity and frequency of rainfall events (Campbell *et al*., 2011). In addition, projections include greater variability in rainfall patterns during November to January, with the northern Caribbean region receiving more rainfall than in the southern Caribbean (Campbell *et al*., 2011). There may be water shortages during drought periods, and flooding after episodes of heavy rainfall, both of which affect the breeding habitats of *Ae. aegypti* and *Ae. albopictus*. Vector control strategies will need to be planned and managed astutely to systematically reduce mosquito populations.

_____ END BOX 11-3 HERE _____

11.5.1.3.Tick-Borne Diseases

These include tick-borne encephalitis (TBE) and *Lyme borreliosis* (LB). TBE, is caused by tick-borne encephalitis virus, and is endemic in temperate regions of Europe and Asia. Western Siberia has the highest incidence of the disease in the world. Asian countries affected by TBE include China, Japan, Mongolia, and South Korea. Lyme disease is an acute infectious disease caused by the spirochaete bacteria *Borrelia burgdorferi* and is reported in Europe, the USA and Canada. *Borrelia* is transmitted to humans by the bite of infected ticks belonging to a few species of the genus *Ixodes* ("hard ticks"). Many studies have found that climate may have an influence on the distribution of tick-borne diseases (Okuthe and Buyu, 2006; Lukan *et al*., 2010; Tokarevich *et al*., 2011; Estrada-Peña *et al*., 2012; Andreassen *et al*., 2012)**.**

In North America, there is good evidence of northward expansion of the distribution of the tick vector (*Ixodes scapularis*) in the period 1996 to 2004 based on an analysis of active and passive surveillance data (Ogden *et al*., 2010). However, there is no evidence so far of any associated changes in the *distribution* in North America of human cases of tick-borne diseases.

Studies since AR4 have confirmed a marked rise in TBE cases since the 1970s in central and Eastern Europe. Spring-time daily maximum temperatures rose in the late 1980s, sufficient to encourage transmission of the TBE virus. Variations in illness rates across the region demonstrate that climate change alone cannot explain the increase, and socioeconomic changes (including changes in agriculture and recreational activities), have strongly affected patterns of disease (Sumilo *et al*., 2008; Randolph, 2010). In the Czech Republic, between 1970 and 2008, there are signs of lengthening transmission season and higher altitudinal range in association with warming (Kriz *et al*., 2012). However, the complex ecology and epidemiology of tick-borne diseases such as *Lyme borreliosis* and TBE make it difficult to attribute particular changes in disease frequency and distribution to specific environmental factors such as climate (Gray *et al*., 2009).

11.5.1.4. Other Vector-Borne Diseases

Hemorrhagic fever with renal syndrome (HFRS) is a zoonosis caused by the Hanta virus, and leads to approximately 200,000 hospitalized cases each year. The incidence of this disease has been associated with temperature, precipitation, and relative humidity (Fang *et al*., 2010; Liu *et al*., 2011). Plague, one of the oldest diseases known to man, remains endemic in many natural epidemic foci around the world. Outbreaks have been linked to seasonal and inter-annual variability in climate (Stenseth *et al*., 2006; Nakazawa *et al*., 2007; Holt *et al*., 2009; Xu *et al*., 2011). Chikungunya fever is another climate-sensitive mosquito-transmitted viral disease, (Anyamba *et al*., 2012) first identified in Africa, now present also in Asia, and recently emerging in parts of Europe (Angelini *et al*., 2008).

11.5.1.5. Near-Future Impacts

Using the A1B climate change scenario, Béguin et al. (2011) projected differences in the population at risk of malaria to 2030 and 2050. If there was no change in GDP per capita, the model projected 5.2 billion people at risk in 2050, out of a predicted global population of 8.5 billion. The additional malaria transmission areas are shown in red in Figure 11-5. Keeping climate constant, and assuming strong and equitable economic growth, would lead to 1.74 billion people at risk (approximately half the present number at risk). Factoring in climate change would increase the "best case" estimate of the number of people at risk of malaria in 2050 to 1.95 billion, which is 200 million more than if disease control efforts were not opposed by higher temperatures and shifts in rainfall patterns.

[INSERT FIGURE 11-5 HERE
Figure 11-5: Contraction of the area of malaria transmission if economic development progresses as forecast (top panel, in blue); expansion in areas of transmission through higher temperatures (bottom panel, in red). Based on IPCC scenario A1B, projections to 2050. Source: Béguin *et al*. (2011).]

There are no studies that project the return of established malaria to Northern America or Europe, where it was once prevalent. Although suitable vectors for *P. vivax* malaria abound in these parts of the world, the risk of re-introduction is thought to be very low, barring civil strife or a breakdown of health services.

We could identify only one study published since 2006 that models future risk of dengue under climate change. Åström (2012) estimated the population at risk out to the year 2050. The study was based on routine disease reports, surveys, population projections, estimates of GDP growth and the A1B scenario for climate change. Three global circulation models were run to 2050, at which time, 4.86 billion people were projected to live in areas at risk of dengue - 6.1% or 280 million more than would have been expected otherwise. Under scenarios of high GDP growth, the number exposed to dengue in 2050 falls to 4.46 billion, ie the adverse effects of climate change are balanced by the beneficial outcomes of development. This study considered only the margins of the geographic distribution of

dengue (where economic development has its strongest effect) and did not examine changes in intensity of transmission in areas where the disease is already established.

Kearny (2009) used biophysical models to examine the potential extension of vector range in Australia. He predicted that climate change would increase habitat suitability throughout much of Australia. Changes in water storage as a response to a drier climate may be an indirect pathway, through which climate change affects mosquito breeding (Beebe *et al.*, 2009).

11.5.2. Food and Water-Borne Infections

Human exposure to climate-sensitive pathogens occurs by ingestion of contaminated water or food, incidental ingestion during swimming or by direct contact with eyes, ears or open wounds. Pathogens in water may be concentrated by bivalve shellfish (e.g., oysters) or deposited on irrigated food crops. Pathogens of concern for waterborne exposure may be enteric and transmitted by the fecal oral route (enteric viruses, bacteria and protozoa) or may occur naturally in aquatic systems (bacteria and protozoa). Climate may act directly by influencing growth, survival, persistence, transmission or virulence of pathogens; indirect influences include climate-related perturbations in local eco-systems and/or the habitat of species that act as zoonotic reservoirs.

11.5.2.1. Vibrio

Vibrio is a genus of native marine bacteria that includes a number of human pathogens, most notably *V. cholerae* which causes cholera. Although cholera is unique in that it can be transmitted both by drinking water and by environmental exposure in seawater and seafood, other Vibrio species are solely linked to seawater and shellfish. These primarily include *V. parahaemolyticus* and *V. vulnificus*, with *V. alginolyticus* emerging in importance (Weis, 2011). Risk of infection is influenced by temperature, precipitation and accompanying changes in salinity due to freshwater run off, addition of organic carbon or other nutrients or changes in pH. These factors all affect the spatial and temporal range of the organism and also influence exposure routes (eg direct contact or via seafood).In countries with endemic cholera, there appears to be a robust relationship between temperature and the disease (e.g., (Paz, 2009; Islam, 2009; Reyburn *et al.*, 2011)). In Bangladesh, precipitation has been shown to be predictive of cholera cases, and higher risk is associated with both high rainfall (and stream level) events as well as below threshold rainfall levels (and lower stream levels) (Hashizume, 2008). This bi-modal pattern is hypothesized to be due to increased water-washed contamination during heavy rains and decreased sanitation (and increased direct contamination) during drier events (Hashizume, 2008).

11.5.2.2. Enteric Bacteria and Viruses

Rates of diarrhea have been associated with high temperatures (Kolstad and Johansson, 2011); however, with a few exceptions we do not know the specific cause of the diarrheal illness nor the mechanism for the association with temperature. Exceptions include *Salmonella* and *Campylobacter*, which are among the most common zoonotic food and waterborne bacterial pathogens worldwide and both show distinct seasonality in infection and higher disease rates at warmer temperatures, especially when outbreaks are excluded. The association between climate (especially temperature) and non-outbreak ('sporadic') cases of salmonellosis may, in part, explain seasonal and latitudinal trends in diarrhea (Lake, 2009).

Among the enteric viruses, there are distinct seasonal patterns in infection that can be related indirectly to temperature. Enterovirus infections in the U.S. peak in summer and fall months (Khetsuriani *et al.*, 2006). After controlling for seasonality and interannual variations, hand, foot and mouth disease (caused by coxsackievirus A16 and enterovirus 71), shows a linear relationship with temperature in Singapore with a rapid rise in incidence when the temperature exceeds 32°C (Hii *et al.*, 2011). However, it is not clear what the underlying driver is and if temperature is confounded by other seasonal factors. Other studies have shown that when released into the environment, enterovirus persistence is negatively correlated with temperature (e.g., (Wetz *et al.*, 2004)).

Temperature is directly linked with enteric disease risk in Arctic communities, where rising temperatures and loss of permafrost may result in transport of sewage (which is often captured in shallow lagoons) into groundwater, drinking water sources or other surface waters (Martin, D., B. Belanger, P Gosselin, J Brazeau,C.Furgal and S.Dery, 2007). Additionally, thawing may damage drinking water intake systems (for those communities with such infrastructure) (Hess, 2008). Harper et al. (2011) showed that in coastal Arctic communities in Canada, higher temperatures precede reports of infectious gastroenteritis with high temperatures corresponding with a 3.9-fold increase in clinic visits within 3 weeks; however this trend was not statistically significant.

Rainfall has also been associated with enteric infections. Pathogens are more likely to be taken up by produce crops (eg lettuce) under conditions of both flooding and drought (Ge *et al.*, 2012) and this is reflected also in patterns of illness (Bandyopadhyay *et al.*, 2012). Higher concentrations of enteric viruses have been noted in drinking water (surface and ground) and recreational water following heavy rainfall (e.g., (Futch, 2010; Jofre *et al.*, 2010)). Likewise, cases of hand, foot and mouth disease (echovirus 71 or coxsackievirus A16) in Singapore increase linearly with cumulative rainfall of up to 75 mm per week (Hii *et al.*, 2011). In the Arctic (Canada), rainfall and increased snowmelt were associated with both deterioration in water quality in reservoirs (evidenced by fecal indicator bacteria) and increased clinic visits for infectious gastroenteritis (Harper *et al.*, 2011).

Illness caused by infection with the rotavirus caused about 450,000 deaths in children under 5 years old in 2008 (Tate *et al.*, 2012). There are seasonal peaks in the number of cases in temperate and subtropical regions but less distinct patterns are seen within 10º latitude of the equator (Cook *et al.*, 1990). Variations in the timing of peak outbreaks between countries or regions (Turcios *et al.*, 2006; Atchison *et al.*, 2010) and variations with time in the same country (Dey *et al.*, 2010) have been attributed to fluctuations in the number and seasonality of births (Pitzer *et al.*, 2009; Pitzer *et al.*, 2011). While vaccination against rotavirus is expected to reduce the total burden of disease, it may also increase seasonal variation (Tate *et al.*, 2009; Pitzer *et al.*, 2011).

11.5.2.3.Near-Term Future

Kolstand and Johansson (2011) project an increase of 8-11% in the risk of diarrhea in the tropics and subtropics due to climate change, up to 2039. In 2040-69 and 2070-99, Kolstad and Johansson projected risk increases of 15-20% and 22-29% respectively using the A1B scenario and 19 coupled atmosphere-ocean climate models from the World Climate Research Programme Coupled Model Intercomparison Project (CMIP3). This study did not projections for economic growth and social development.

Zhou *et al.* (2008) estimated the transmission of schistosomiasis due to *S. japonicum* in China based on rising temperatures in 2030 and 2050. They concluded that an additional 784 thousand km^2 would become suitable for schistosomiasis transmission in China by 2050 (Figure 11-6).

[INSERT FIGURE 11-6 HERE
Figure 11-6: Projected risk map of schistosomiasis*(S. japonicum)* transmission in China in 2050. For comparison the current risk map in 2000. Green area denotes the range of schistosomiasis in 2000. The blue area shows the geographic expansion. Adapted from (Zhou *et al.*, 2008).]

Mangal et al. (2008) constructed a mechanistic model of the transmission cycle of another species, *S. mansoni* and reported a peak in the worm burden in humans at an ambient temperature of 30°C, falling sharply as temperature rises to 35°C. The authors attribute this to the increasing mortality of both the snails and the water-borne intermediate forms of the parasite, and noted that worm burden is not directly linked to the prevalence of schistosomiasis.

11.5.3. Air Quality

Nearly all the non-CO_2 climate-altering pollutants (CAPs – see Ch x of WGI) are health damaging, either directly or by contributing to secondary pollutants in the atmosphere. Thus, like the ocean acidification and ecosystem/ agriculture fertilization impacts of CO_2, the other CAPs have non-climate-mediated impacts, particularly on health. Although not reviewed in detail in this assessment, the health impacts of non-CO_2 CAPs are substantial globally. See Box 11-4.

_____ START BOX 11-4 HERE _____

Box 11-4. Health and Economic Impacts of Climate-Altering Pollutants (CAPs) Other than CO_2

Although other estimates of the global health impacts of human exposures to particle and ozone pollution have been done in recent years (e.g.(UNEP, 2011)), the most comprehensive was the Comparative Risk Assessment carried out as part of the Global Burden of Disease Project (Lim *et al*., 2012). It found that the combined health impact of the household exposures to particle air pollution from poor combustion of solid cooking fuels plus general ambient pollution was about 6.8 million premature deaths annually, with about half a million overlapping, i.e., coming from the contribution to general ambient pollution of household fuels. It also found that about 150 thousand premature deaths could be attributed to ambient ozone pollution. Put into DALY terms, particle air pollution was responsible for about 190 million lost DALYs in 2010, or about 7.6% of all DALYs lost. This burden puts particle air pollution among the largest risk factors globally, far higher than any other environmental risk and rivaling or exceeding all of the five dozen risk factors examined, including malnutrition, smoking, high blood pressure, and alcohol.

The economic impact of this burden is difficult to assess as evaluation methods vary dramatically in the literature. Most in the health field prefer to consider some version of a lost healthy life year as the best metric although the economics literature often uses willingness to pay for avoiding a lost life (Jamison *et al*., 2006). Another difficulty is that any valuation technique that weights the economic loss according to local incomes per capita will value health effects in rich countries more than in poor countries, which would seem to violate some of the premises of a global assessment; see WGIII, ch 3 for more discussion. Here, however, we will use the mean global income per capita (~ USD 10,000 in 2010) to scope out the scale of the impact globally without attempting to be specific by country or region.

The WHO CHOICE approach for evaluating what should be spent on health interventions indicates that one annual per capita income per DALY is a reasonable lower bound (World Health Organization, 2009b). This would imply that the total lost economic value from global climate-altering pollutants in the form of particles is roughly USD 1.9 trillion, in the sense that the world ought to be willing to pay this much to reduce it. This is about 2.7% of the global economy (approximately USD 70 trillion in 2010).

On the one hand, this shows that global atmospheric pollution already has a major impact on the health and economic well-being of humanity today, due mainly to the direct effects rather than those mediated through climate. If CO_2 is not controlled and climate change continues to intensify while air pollutant controls become more stringent, the climate impacts will become more prominent. The quite different time scales for the two types of impacts make comparisons difficult, however.

Unfortunately, the twin goals of protecting health and climate do not always lead to congruent actions. All particles are dangerous for health, but some are cooling, such as sulfates, and some warming, such as black carbon (Smith *et al*., 2009). Indeed, as indicated in WGI (Ch x), elimination of all anthropogenic particles in the atmosphere, a major success for health, would have only a minor net impact on climate. As discussed in the co-benefits section below (11.9), there are nevertheless specific actions that will work toward both goals.

_____ END BOX 11-4 HERE _____

Although there is a large literature on the health effects of particle air pollution (see Box 11-4), WGI indicates that there is little evidence that climate change, per se, will affect long-term particle levels in a consistent way. Thus, we

focus here on chronic ozone exposures, which are found in WGI (Ch x) to be enhanced in some scenarios of future climate change.

11.5.3.1. Long-Term Outdoor Ozone Exposures

Tropospheric ozone is formed through photochemical reactions that involve nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), and volatile organic compounds (VOCs) in the presence of sunlight and elevated temperatures (US EPA, 2007). Therefore, if temperatures rise, many air pollution models (Ebi and McGregor, 2008; Tsai *et al.*, 2008; Chang *et al.*, 2010; Polvani *et al.*, 2011) project increased ozone production especially within and surrounding urban areas (Hesterberg *et al.*, 2009). Even small increases in atmospheric concentrations of ground-level ozone may affect health (Bell *et al.*, 2006; Ebi and McGregor, 2008; Jerrett *et al.*, 2009). For instance, Bell et al. (2006) found that even levels that meet the US EPA 8-hour regulation (0.08 ppm over 8 hours) were associated with increased risk of premature mortality. There is a lack of association between ozone and premature mortality only at very low concentrations (from 0 to ~10 ppb) but the association becomes positive and approximately linear at higher concentrations (Bell *et al.*, 2006; Ebi and McGregor, 2008; Jerrett *et al.*, 2009). In an analysis of 66 United States cities with 18 years of follow-up (1982-2000), ozone was found to be significantly associated with cardiopulmonary mortality (Smith *et al.*, 2009). See also the global review by WHO, which includes data from developing countries (WHO 2006).

11.5.3.2. Acute Air Pollution Episodes

Wildfires, which may increase under climate change, release large amounts of particulate matter and other toxic substances that may affect larger numbers of people (Handmer *et al.*, 2012; Finlay *et al.*, 2012)**.** During a fire near Denver (USA) in June 2009, 1-hour concentrations of PM_{10} and $PM_{2.5}$ reached 370 $\mu g/m^3$ and 200 $\mu g/m^3$, and 24-hour average concentrations reached 91 $\mu g/m^3$ and 44 $\mu g/m^3$, compared to the 24-hour WHO air quality guidelines for these pollutants of 50 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively (Vedal and Dutton, 2006).

One study of world-wide premature mortality attributable to air pollution from forest fires estimated there were 339,000 deaths per year (range 260,000 to 600,000) (Johnston *et al.*, 2012). The regions most affected are Sub-Saharan Africa and Southeast Asia (Johnston *et al.*, 2012).

Extremely high levels of PM_{10} were observed in Moscow due to forest fires caused by a heat wave in 2010. Daily mean temperatures in Moscow exceeded the respective long-term averages by 5°C or more for 45 days and 10 new temperature records were established in July and 9 in August, based on measurements since 1885, and an anti-cyclone in the Moscow region prevented dispersion of air pollutants. The highest 24-h pollution levels recorded in Moscow during these conditions were between 430 and 900 $\mu g/m^3$ PM10 most days, but occasionally reached 1500 $\mu g/m^3$. The highest 24-h CO concentration was 30 mg/m^3 compared to the WHO AQG of 7 $\mu g/m^3$, and the levels of formaldehyde, ethyl benzene, benzene, toluene and styrene were also increased (State Environmental Institution "Mosecomonitoring", 2010).

There is an interaction of ozone and heat waves as well. Dear et al. (2005) modeled the daily mortality on heat and ozone during the European summer heatwave of 2003 and found that possibly 50% of the deaths could have been associated with ozone exposure rather than the heat itself.

11.5.3.3. Aeroallergens

Allergic diseases are common and are climate-sensitive. Warmer conditions generally favour the production and release of air-borne allergens (such as fungi and lower plant spores and pollen) and, consequently, there may be an effect on asthma and other allergic respiratory diseases, such as asthma, allergic rhinitis, conjunctivitis and dermatitis (Beggs et al, 2010). Children are particularly susceptible to most allergic diseases (Schmier and Ebi, 2009). Increased release of allergens may be amplified if higher CO_2 levels stimulate plant growth. Visual

monitoring and experiments have shown that increases in air temperature cause earlier flowering of prairie tallgrass (Sherry *et al*., 2007). Droughts and high winds may produce windborne dust and other atmospheric materials, which contains pollen and spores, and transport these allergens to new regions.

Studies have shown that increasing concentrations of grass pollen lead to more frequent ambulance calls due to asthma symptoms, with a time lag of 3-5 days (Heguy *et al*., 2008). Pollen levels have also been linked to hospital visits with rhinitis symptoms (Breton *et al*., 2006). A cross-sectional study in the three climatic regions of Spain documented a positive correlation between the rate of child eczema and humidity, and negative correlation between child eczema and air temperature or the number of sunshine hours (Suarez-Varela *et al*., 2008).

11.5.3.4.Near-Term Future

It is projected by WGI that climate change could affect future air quality, including levels of photochemical oxidants and, with much less certainty, fine particles ($PM_{2.5}$). If this occurs there will be consequences for human health. (Bell *et al*., 2007; Dong *et al*., 2011; Chang *et al*., 2012; Lepeule *et al*., 2012; Meister *et al*., 2012). High temperatures may also magnify the effects of ozone (Ren *et al*., 2008; Jackson *et al*., 2010). Increasing urbanization, use of solid biomass fuels and industrial development in the absence of emission controls could also lead to increases in ozone chemical precursors (Selin *et al*., 2009; Wilkinson *et al*., 2009).

Most post-2006 studies on the projected impacts of future climate change on air pollution-related morbidity and mortality have focused on ozone (see Table 11-2; Bell *et al*., 2007; Selin *et al*., 2009; Tagaris *et al*., 2009). Most studies focus on Europe, the U.S. and Canada. Projections are rare for other areas of the world, notably the developing countries where air pollution is presently a serious problem and is expected to get worse.

[INSERT TABLE 11-2 HERE
Table 11-2: Projected future health impacts of climate change through air pollution.]

Higher temperatures may magnify the effects of air pollutants like ozone, although estimates of the size of this effect vary (Ren *et al*., 2008; Jackson *et al*., 2010). In general, all-cause mortality related to ozone is expected to increase in the US and Canada (Bell *et al*., 2007; Tagaris *et al*., 2009; Jackson *et al*., 2010; Cheng *et al*., 2011). Under a scenario in which present air quality legislation is rolled out everywhere, premature deaths due to ozone would be wound back in Africa, South Asia and East Asia. Under a maximum feasible CO_2 reduction scenario related to A2, it is projected that 460,000 premature ozone-related deaths could be avoided in 2030, mostly in South Asia (West *et al*., 2007).

A study that investigated regional air quality in the United States in 2050, using down-scaled climate model (Goddard Institute for Space Studies, Global Climate Model), concluded there would be about 4000 additional annual premature deaths due to increased exposures to $PM_{2.5}$ (Tagaris *et al*., 2009). Air pollutant-related mortality increases are also projected for Canada but in this case they are largely driven by the effects of ozone (Cheng *et al*., 2011)On the basis of the relation of asthma to air quality in the last decade (1999-2010), Thompson et al. (2012) anticipate that the prevalence of asthma in South Africa will increase substantially by 2050. Sheffield et al. (2011), applying the SRES A2 scenario, projected a median 7.3% increase in summer O_3-related asthma emergency department visits for children (0-17 years) across New York City by the 2020s compared to the 1990s.

11.6. Health Impacts Heavily Mediated through Human Institutions

11.6.1. Nutrition

At its most simple, nutrition can be considered as resulting from the interaction of three main elements: agricultural production (net of post-harvest wastes and storage losses), governance and human disease, especially those which affect appetite, nutrient absorption and catabolism (Black *et al*., 2008; Lloyd *et al*., 2011). Many of these factors are

influenced by climate. Malnutrition, referring to insufficient nutrient intake, is also related very closely to a temporary or long-term ability to pay for sufficient food, i.e., poverty.

11.6.1.1.Mechanisms

See Chapter 7 for a discussion of the impact of climate change on agricultural production.

The magnitude of detected decline in land-based agricultural production due to increasing temperatures and changes in rainfall is small compared to the increase in harvests due to improved farming knowledge and technology (Lobell *et al.*, 2011). It is also minor in comparison to the amount of food fed to livestock, used for biofuels, consumed beyond baseline needs by the overnourished and wasted in other ways (Foley *et al.*, 2011). Against this background, the global food price fluctuates, though with a recently rising trend. While the main driver is higher energy costs, amplified by speculation, (Piesse and Thirtle, 2009) there is growing speculation (Auffhammer, 2011) that extreme weather events, especially floods, droughts (Williams and Funk, 2011) and heatwaves have contributed to higher prices, which, all else being equal, will increase the number of malnourished people.

The modeling of past and future agro-climatic effects, even without considering their health impact, is a formidable challenge, and some argue the existing agro-climate models are excessively simple and biased toward the optimistic (Butler, 2010; Gornall *et al.*, 2010). Moreover, the strength of the carbon fertilization effect (CFE) may have been overstated (Long *et al.*, 2006; Leakey *et al.*, 2008). Higher concentrations of CO_2 may also enhance the growth of pests (Ziska *et al.*, 2009; Nelson *et al.*, 2009; Nelson *et al.*, 2010) and damage some crops, including cassava, a staple for about 750 million mostly poor people (Gleadow *et al.*, 2009). These effects to date are generally not incorporated into models.

11.6.1.2.Near-Term Future

Since AR4 four studies have been published which project the effect of climate change on food availability (undernourishment) and malnutrition (acute and chronic).[3] It is important to distinguish between undernourishment (hunger), caused by lack of food, and malnutrition which is due not only to food intake but to other factors (eg chronic infections).

[FOOTNOTE 3: In technical terms, these are called “wasting” (acute) and “stunting” chronic. The former is measured as deviations from the weight for height, the latter from weight for age.]

Ebi (2008) projected the climate-attributable numbers of malnourished children to 2030 and reported a 10% (4,673,000 cases) increase against the counterfactual of no climate change. Nelson et al. (2009; 2010) built a global agricultural supply and demand projection model (IMPACT 2009) and a crop simulation model (DSSAT) to estimate crop production, with and without CO_2 enrichment. The authors projected per capita calorie under climate models from NCAR and CSIRO (the world projected in the former is wetter and dryer). The authors estimate that there would be about 25 million additional malnourished children in 2050 with climate change (Nelson *et al.*, 2009), focusing on the effect of investment in agricultural productivity (see Table 11-3). In those parts of the world most affected by under- and mal-nutrition (Sub-Saharan Africa and the Middle East and North Africa), comprehensive investments in agriculture would reduce the anticipated impact of climate change, but not entirely.

[INSERT TABLE 11-3 HERE
Table 11-3: Number of malnourished children less than 5 years of age (in millions) in 2000 and under the NCAR climate model (using A2 scenario from AR4) till 2050. Assumptions for investment in agricultural productivity: + only in developing countries; ++ both in developing and developed countries. Results assume no CO_2 fertilization effects. Adapted from Nelson *et al.* (2009).]

Lloyd et al. (2011) built a model for estimating future undernourishment (too little food) and child malnutrition (stunting), under two climate change scenarios and a reference scenario without climate change. While the estimates

of undernourished children were based on food availability projections from Nelson et al. (2009), stunting was modeled using "food" and "non-food" causes. The increase in severe stunting attributable to climate change in 2050 ranged from 31% in central Sub-Saharan Africa to 62% in South Asia. The comparison was a world without climate change, in which the numbers of undernourished and stunted children fell. The authors concluded that climate change will hold back efforts to reduce child malnutrition in the most severely affected parts of the world, even with allowances for economic growth.

In a subsequent paper, Lloyd et al. (2011) estimated the number of malnutrition-attributable childhood deaths. The relationship between severity of stunting and mortality was drawn from Black et al. (2008). For 2030, their model projected 108,028 malnutrition-related childhood deaths from climate change (8.0% out of a total of 1,256,440 malnutrition-related deaths). For 2050, they estimated this number to be 96,460 out of 614,361 (15.7%). Hence, while the absolute number of children dying from malnutrition would fall by half between 2030 and 2050 due to social and economic development, the proportion attributable to climate change would double.

Grace et al (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability as well as child stunting in Kenya. The authors conclude that climate change will increase the proportion of small-for-age children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial investments in education and infrastructure.

In summary, we have high confidence that climate change will have a substantial negative impact on (i) per capita calorie availability, (ii) childhood malnutrition, particularly stunting and (iii) on malnutrition–related child deaths and DALYs lost (high agreement with medium evidence).

11.6.2. Occupational Health

Since the AR4 much has been written on the effects of heat on working people (Kjellstrom *et al*., 2009a; Dunne *et al*., 2013) and on other climate-related occupational health risks (Bennett and McMichael, 2010).

11.6.2.1. Heat Strain and Heat Stroke

The basic processes of human thermoregulation are well-understood (Parsons, 2003). If the body temperature goes beyond 38°C, performance may be impaired. Temperature above 39°C risks symptoms of "heat stroke": organ damage, loss of consciousness, and death. Pre-existing disease or malnutrition increases vulnerability. Experimental and field studies have documented the risks of excessive heat exposure (Ramsey and Bernard, 2000; Parsons, 2003) and detailed exposure response relationships were described long ago (Wyndham, 1969). Heat remains an occupational health issue even in a high-income country like the USA (Luginbuhl *et al*., 2008). Moreover, at higher temperatures there is potential conflict between health protection and economic productivity (Kjellstrom *et al*., 2011): as workers take longer rests to prevent heat stroke, hourly productivity goes down.

11.6.2.2. Heat Exhaustion and Work Capacity Loss

There are international standards of maximum recommended workplace heat exposure and hourly rest time (e.g. (ISO, 1989; Parsons, 2003)) for both acclimatized and non-acclimatized people. In hot countries during the hot season, large proportions of the workforce are affected by heat, and the economic impacts of reduced work capacity may be sufficient to jeopardize livelihoods (Lecocq and Shalizi, 2007; Kjellstrom *et al*., 2009a; Kjellstrom *et al*., 2011; Kjellstrom and Crowe, 2011). Kjellstrom et al. (Kjellstrom *et al*., 2009a; Kjellstrom and Crowe, 2011; Kjellstrom *et al*., 2011) and Dunne et al. (Dunne *et al*., 2013) estimate that loss of work productivity during the hottest and wettest seasons has already occurred, at least in Asia and Africa.

11.6.2.3. Other Occupational Health Concerns

Exposure to heat affects psychological performance (Hancock *et al.*, 2007) and increased risk of injuries (Ramsey, 1995). In areas where vector-borne diseases, such as malaria and dengue fever, are common, people working in fields without effective protection may experience a higher incidence of these diseases when climatic conditions favour mosquito breeding and biting (Bennett and McMichael, 2010). Increasing heat exposure in farm fields during the middle of the day may lead to more work during dawn and dusk when some of the vectors are biting humans more actively.

Another risk factor is increased chemical poisoning where solvents are used, because higher temperatures make the solvents evaporate faster and may lead to higher occupational exposures (Bennett and McMichael, 2010). In the Arctic, the part of the world that is now experiencing the fastest increase of temperatures, traditional hunting and fishing activities are affected by reduction in sea ice and there is a greater risk of drowning (Ford *et al.*, 2008).

11.6.2.4. Near-Term Future

Projections have been made of the future effects of heat on work capacity (Kjellstrom *et al.*, 2009b; Dunne *et al.*, 2013). Temperature and humidity were both included, and the modeling took into account the changes in the workforce distribution relating to the need for physical activity. In South East Asia in 2050 the model indicates that more than half the afternoon work hours will be lost due to the need for rest breaks (Kjellstrom *et al.*, 2013). By 2100, under RCP4.5 Dunne et al. (2013) project up to 20% loss of productivity globally. There is an unfortunate trade-off between health impact and productivity loss, which creates risks for poor and disenfranchised laborers working under difficult working conditions and inflexible rules (Kjellstrom *et al.*, 2009a; Kjellstrom *et al.*, 2011).

11.6.3. Mental Health

Mental illness, a major contributor to the global burden of disease, (Mathers and Loncar, 2006) leads to functional impairment and disordered behaviour in domains as diverse as crime, housing, employment, relationships, violence, education, physical health, substance use and health behaviours. Poor mental health is associated in general with lower levels of resilience, coping and adaptive capacity. Overwhelmed by repeated disasters, an increasing numbers of people may lose hope, as appears to happen with farmers facing severe drought (Berry *et al.*, 2011).

Manifestations of disaster-related psychiatric trauma include severe anxiety reactions (such as post-traumatic stress) and longer-term impacts such as generalised anxiety, depression, aggression and complex psychopathology (Ahern *et al.*, 2005). For slow-developing events such as prolonged droughts, impacts include chronic psychological distress and increased incidence of suicide (Hanigan *et al.*, 2012; O'Brien *et al.*, Under review)(Alston, 2008).

Harsher weather conditions increase the stress on those who are already mentally ill, worsening their condition and prognosis; and may create sufficient stress for some who are not yet ill to become so (Berry *et al.*, 2010b). Functional impairment means diminished population-level resilience, adaptive capacity and coping. There may be impacts on agricultural productivity, fishing, forestry, tourism, mining, subsistence farming and other economic endeavours reliant on the land. As more than half the world's population now lives in cities, disasters such as cyclones, heatwaves and major floods can easily stress or destroy infrastructure and take lives *en masse*, by affecting whole zones of cities. Here again, the vulnerable are most at risk: cities have zones of concentrated disadvantage (where mental disorders are disproportionately prevalent) (Berry, 2007) and these typically lie on the least advantageous land, land that is most prone to disaster (such as flood plains). Impacts on infrastructure and immediate loss of life, in turn, compromise local industries, businesses and households; and when these face extreme pressure, livelihoods, families and eventually whole communities can struggle to cope. Of particular importance, to the extent that deteriorating community functioning involves loss of social capital, mental health will be at risk because the presence of social capital is strongly protective for health, especially for mental health. (Berry *et al.*, 2010b).

The impacts of extreme weather events on mental health are broad-ranging: Major Depressive Disorder is the most common disorder, followed by Post-Traumatic Stress Disorder, other anxiety disorders and, mental distress. (Crabtree, 2012). A cyclone and flooding disaster in Queensland, in 2010-11 cost that Australian state US$7 billion in infrastructure repairs alone with consequences for livelihoods and health. Disadvantaged communities received the most damage to homes, businesses and incomes *and* reported higher rates of trauma-related impact per traumatic exposure than did less disadvantaged respondents (Clemens *et al.*, in preparation). That is, there was a linear dose-response effect for all victims but the response was significantly larger for disadvantaged communities. Two years later, another flood event affected that state before these same communities had recovered from the first.

In addition to indirect effects on mental health via the risk/disadvantage cycle, extreme weather events may adversely affect mental health *directly*, through immediate psychiatric trauma, heat impacts on certain classes of psychiatric medication), and a distressing sense of loss, known as 'solastalgia', that people experience when 'their' land is damaged (Albrecht *et al.*, 2007) and they lose amenity and opportunity.

11.6.4. Violence and Population Displacement

A study in Milwaukee, Wisconsin reported temperatures above 27.2°C were associated with increased accidents and self-harm (Li, T., Horton, R., Kinney,P., 2011). In Adelaide, South Australia, assault-related injuries among 15–64 year-olds increased significantly during heat waves (Nitschke *et al.*, 2007), and others have reported a relationship between high temperatures and increased risk of suicide. (Page *et al.*, 2007). Changes in behavior in times of extreme temperatures, however, may reduce the risks of some forms of injury. For example, in South Australia a significant decrease in automobile accidents was found during heat waves in the 75+ age group (Nitschke *et al.*, 2007).

Soil degradation, freshwater scarcity, population pressures and other forces that are related to climate are all potential causes of conflict. A study of internal conflict in African countries from 1981-2002 found a positive correlation between country-level temperature increases and probability of armed conflict and suggested that the effects of temperature change on agriculture might be a significant factor (Burke *et al.*, 2010). The relationships are not straightforward, however, as many factors influence conflict and violence. A study drawing on data from 1960-99, including more than 160 countries, found that poverty, low economic growth and high dependence on primary commodity exports were strongly associated with civil war, while ethnic and religious diversity as well as democracy were not (Collier and Hoeffler, 2004). The resultant ambiguity has recently led to more highly specified models that take account of variables such as social networks, indigenous knowledge and family cohesion that reduce vulnerability to climate disasters (Adger *et al.*, 2003). In Sub-Saharan Africa it has been reported climates that are more suitable for agriculture are associated with a lower risk of conflict (Hendrix and Glaser, 2007). Another study argues that environmentally induced migration can increase the risk of conflict, particularly in less-developed countries, and the risk is compounded by rapid population growth and limited migration opportunities (Reuveny, 2007).

Impacts of drought on human health also occur largely through indirect pathways; such as impacts on agriculture and population displacement (MacDonald, 2010; Kolmannskog, 2012).

Although the relationship between climate and armed conflict should not be overstated, in view of other social, cultural, political and economic factors that play a part, there is ample evidence that the depletion and altered distribution of natural resources may heighten the risk of violent conflict (Brauch, 2002; Oberthür *et al.*, 2002). Using data from 1950 to 2004 from the tropics, Solomon et al. (2010) found that the probability of new civil conflicts arising doubles during El Niño years relative to La Niña years. A study of a thousand years of violent conflict in Europe and various reconstructions of temperature and precipitation, found that conflict was exacerbated during cold periods that were associated with crop failures and food shortages (Tol and Wagner, 2010). Similar findings have been reported in China (Zhang *et al.*, 2006), and indeed the links between rapid climate change, starvation and civil disorder and collapse are apparent as far back as the first agricultural settlements roughly 10,000 years before the present (McMichael *et al.*, 2012).

11.7. Adaptation to Protect Health

Life expectancies and years of healthy life have increased considerably over the past century due to improvements in public health and health care strategies, policies, and measures, due to greater understanding of the complex factors driving adverse health conditions, as well as actions in other sectors, such as providing access to safe water and improved sanitation. In some situations, climate variability and change threatens continuing advances in reducing the burden of climate-sensitive health outcomes. The degree to which programs and measures will need modification to address any additional pressures from climate change will depend on factors such as the current burden of climate-sensitive health outcomes, the effectiveness of current interventions, projections of where, when, and how the health burden could change with climate change, the feasibility of implementing additional programs, other stressors that could increase or decrease resilience, and the social, economic, and political context for intervention (Ebi *et al*., 2006). The process of adaptation will be on-going adjustments to the degree and rate of climate change and other factors driving the incidence and geographic range of climate-sensitive health outcomes.

The scientific literature on adaptation to climate change has expanded since AR4, but investment in specific health protection activities is growing less rapidly. A review by the World Health Organization in 2012 estimated that commitments to health adaptation internationally amount to less than 1% of the annual health costs attributable to climate change in 2030 (World Health Organization, 2012).

The value of adaptation is demonstrated by the population health impacts of recent disasters associated with extreme weather and climate events. For example, more than 500,000 people died when cyclone Bhola (category 3 in severity) hit East Pakistan (present day Bangladesh) in 1970. In 1991, a cyclone of similar severity caused about 140,000 deaths. In November 2007, cyclone Sidr (category 4) resulted in 5-10,000 deaths even though the population had grown by more than 30 million in the intervening period (Mallick *et al*., 2005). Bangladesh achieved this remarkable reduction in mortality through effective collaborations between governmental and non-governmental organizations and local communities (Khan, 2008). Alongside improving general disaster education (greatly assisted by rising literacy rates, especially among women), the country deployed early warning systems and built a network of cyclone shelters. Early warning systems included both high technology information systems and relatively simple measures such as training volunteers who could distribute warning messages by bicycle.

Efforts to adapt to the health impacts of climate change can be categorized as incremental, transitional, and transformational actions (O'Brien *et al*., 2012). Incremental adaptation occurs when information on the risks of climate change is integrated into policies and measures, without changing underlying assumptions. This includes improving public health and health care services for climate-sensitive health outcomes, without necessarily considering the possible impacts of climate change. Transitional adaptation occurs with changes in underlying assumptions, including shifts in attitudes and perceptions. This includes vulnerability mapping, early warning systems, and other measures. Transformation occurs with changes in social and other structures that mediate the construction of risk.

11.7.1. Improving Basic Public Health and Health Care Services

Because the baseline health status of a population may be the single most important predictor of the future health impacts of climate change and the costs of adaptation (Pandey, 2010), reducing background rates of disease and injury is an important step to improving population resilience and minimizing poor health outcomes from climate change.

Most health adaptation is focusing on improvements in basic public health functions to reduce the current adaptation deficit, such as enhancing disease surveillance, monitoring risky exposures, and facilitating coordination between health and other sectors to address shifts in the incidence and geographic range of diseases (Woodward *et al*., 2011). An example is Lusaka, Zambia, where the incidence of cholera rises sharply following heavy rainfall, with lower risk in parts of the city with effective drainage networks (Sasaki *et al*., 2009).

Health care interventions may reduce harm caused by climate and other environmental stressors. As one example, following the introduction of vaccination programs in the United States, seasonal outbreaks of rotavirus, a common climate-sensitive pathogen, were delayed and diminished in magnitude (Tate *et al*., 2009). Post-disaster initiatives also are important. For example, an assessment of actions to improve the resilience of vulnerable populations to heatwaves recommended staff planning over the summer period, cooling of health care facilities, training of staff to recognize and treat heat strain, and monitoring of those in the highest risk population groups (World Health Organization Regional Office for Europe, 2009). Similarly, diabetes care was compromised following Hurricane Katrina in the United States by a lack of blood glucose testing kits, and insulin and other diabetes medications (Cefalu *et al*., 2006). Ensuring essential medical supplies for care of individuals with chronic conditions, including effective post-disaster distribution, would increase the ability of communities to manage large-scale floods and storms. Another example is in Benin, where one measure proposed as part of the national response to sea level rise and flooding is expanded health insurance arrangements, so that diseases such as malaria and enteric infections can be treated promptly and effectively (Dossou and Glehouenou-Dossou, 2007).

11.7.2. Health Adaptation Policies and Measures

Transitional adaptation moves beyond focusing on reducing the current adaptation deficit to designing into programs and measures considerations of how a changing climate could alter health burdens and the effectiveness of intervention actions. Ten "essential public health services" underpin coping with the health risks of climate change (Frumkin *et al*., 2008). For example, maintaining and improving food safety in the face of rising temperatures and rainfall extremes depends on effective interactions between human health and veterinary authorities, integrated monitoring of food-borne and animal diseases, and improved methods to detect pathogens and contaminants in food (Tirado *et al*., 2010). Indicators of community functioning and connectedness are relevant as well, because communities with high levels of social capital tend to be more successful in disseminating health and related messages, ensuring compliance with behavioural norms and providing support to those in need (Frumkin *et al*., 2008).

Vulnerability Mapping

Remote sensing technologies are now sufficiently fine-grained for mapping local vulnerability factors and can be used to guide interventions to reduce exposures and/or impacts. For example, these technologies can be used to map surface temperatures and urban heat island effects at the neighborhood scale, indicating where city greening and other urban cooling measures could be most effective, and alerting public health authorities to populations that may be at greatest risk of heatwaves (Luber and McGeehin, 2008). Mapping at regional and larger scales may be useful to guide adaptation actions. In Portugal, modeling of Lyme disease indicates that future conditions will be less favorable for disease transmission in the south, but more favorable in the center and northern parts of the country (Casimiro *et al*., 2006). This information can be used to modify surveillance programs before disease outbreaks occur. To capture a more complete picture of vulnerability, mapping exercises also should consideration of climate sensitivity and adaptation capacity, such as was done in an assessment of climate change and risk of poverty in Africa (Thornton *et al*., 2008).

11.7.3. Early Warning Systems

Early warning systems have been developed in many areas as a means of alerting public health authorities to climate-related health risks. Effective early warning systems take into consideration the wide range of factors that can drive risk.

Heatwave and health warning systems (HHWS) are designed to prevent negative health impacts. Components of an effective HHWS include forecasting weather conditions associated with increased morbidity or mortality, predicting possible health outcomes, identifying triggers of effective and timely response plans that target vulnerable populations, communicating heatwave and prevention responses, and evaluating and revising the system to increase

effectiveness in a changing climate (Lowe *et al.*, 2011). Of seven studies of the effectiveness of heatwave early warning systems to reduce heat-related mortality, six reported fewer deaths during heatwaves after implementation of the system (Palecki *et al.*, 2001; Weisskopf *et al.*, 2002; Ebi *et al.*, 2004; Tan *et al.*, 2007; Fouillet *et al.*, 2008; Chau *et al.*, 2009); only Morabito et al. (2012) was inconclusive. For example, in the summer of 2006, France experienced high temperatures similar to those experienced during the 2003 heatwave, with about 2000 excess deaths. This was more than 4000 less than was anticipated on the basis of the experience in 2003. A national assessment attributed the lower than expected death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heatwave early warning system (Fouillet *et al.*, 2008). A review of the heatwave early warning systems in the twelve European countries with such plans concluded that evaluations of the effectiveness of these systems is urgently needed to inform good practices, particularly understanding which action increase resilience (Lowe *et al.*, 2011).

Early warning systems also have been developed using predictive models for vector-borne and food-borne infections. In Botswana, an early warning system forecasts malaria incidence up to 4 months in advance based on observed rainfall; inter-annual and seasonal variations in climate are associated with outbreaks of malaria in this part of Africa. Model outputs include probability distributions of disease risk and measures of the uncertainty associated with the forecasts (Thomson *et al.*, 2006). The incidence of several bacterial enteric infections varies with ambient temperature (Fleury *et al.*, 2006); this information has been used to develop health alerts based on projected temperatures. A study of campylobacteriosis in the United States developed models of monthly disease risk with a very good fit in validation data sets (R^2 up to 80%) (Weisent *et al.*, 2010).

11.7.4. Role of Other Sectors in Health Adaptation

Other sectors play an important part in protecting against disease and injury resulting from climate change. EuroHEAT, a European review of public health responses to extreme heat, identified transport policies building design, and urban land use as important elements of national and municipal heatwave and health action plans (World Health Organization Regional Office for Europe, 2009). A study examining well-established interventions to reduce the urban heat island effect (replacing bitumen and concrete with more heat-reflective surfaces, and introducing more green spaces to the city) estimated these would reduce heat-related emergency calls for medical assistance by almost 50% (Silva *et al.*, 2010). Urban green spaces lower ambient temperatures, improve air quality, provide shade, and may be good for mental health (van den Berg *et al.*, 2010). However, the extent to which changes in these factors reduce heatwave-related morbidity and mortality depend on location. A study in London, UK, found that built form and other dwelling characteristics more strongly influenced indoor temperatures during heatwaves than the urban health island effect (Oikonomou and Wilkinson, 2012).

A review of food aid programs indicates that a rapid response to the risk of child under-nutrition, targeted to those in greatest need, with flexible financing and the capacity to rapidly scale-up depending on need, may reduce damaging health consequences (Alderman, 2010).

Community programs designed for other purposes can facilitate adaptation. In the Philippines, for example, interventions in low-income urban settings include savings schemes, small-scale loans, hygiene education, local control and maintenance of water supplies, and neighborhood level solid waste management strategies (Dodman *et al.*, 2010). All these have the potential to reduce the harmful effects of climate extremes on health.

Migration

Migration is a common coping strategy in the face of adverse changes in climate, and may itself have significant effects on health, positive and negative (McMichael *et al.*, 2012)(McMichael et al., 2010). Within the Pacific, there has been migration from outer islands to urban centers, partially due to environmental pressures, improving economic and educational opportunities for some. But there is a cost in infectious diseases and other health problems caused by crowding associated with a lack of adequate water supplies, waste disposal, and housing (Locke, 2009). Large numbers of Pacific islanders have also moved to countries around the Pacific rim and

comparisons of the health of migrants and peers in the islands show mixed effects (higher levels of risk factors such as raised blood pressure and cigarette smoking among migrants, but also lower mortality rates overall and higher life expectancies). Climate-related migration includes the movements of population between countries, and within country shifts, such as flows to cities from drought and heat-affected rural areas (Acosta-Michlik *et al*., 2008). Where people choose to live reflects a complex balance of risks and benefits. Where large numbers of people are forced to migrate at the same time, there may be considerable social, cultural, economic and health implications for receiving communities, particularly where these peoples may be traumatised (McMichael *et al*., 2012). A study in Indore in India found that low-income households were willing to live in flood-prone areas because of other advantages provided by these sites, including access to health care and low-cost housing (United Nations Human Settlements Programme, 2011).

11.8. Limits to Adaptation: Low-Probability Extreme Climates

Most attempts to quantify health burdens associated with future climate change consider relatively short time horizons (e.g. 2030 or 2050) and modest increases in global average temperature, typically less than 2 degrees Celsius during the time frame considered. Because of the longevity of some greenhouse gases in the atmosphere and inertia of the climate system, emissions today will, however, contribute to warming far beyond 2050. Moreover, research published since AR4 raises doubt over whether it will be possible to limit global warming to 2°C above pre-industrial temperatures (Rogelj *et al*., 2009; Anderson and Bows, 2011; PriceWaterhouseCoopers, 2012). Therefore it is important to examine the likely consequences of warming beyond 2 degrees, what we have called high-end warming scenarios (New *et al*. 2011).

It can be assumed that the increase in many important climate-related health impacts at increasingly higher levels of warming will be greater than simple linear increments; that is, that the health consequences of a 4°C temperature increase will be more than twice those of a +2°C world (see Figure 11-7). Nonlinear and threshold effects have been observed in the mortality response to extreme heat (Anderson and Bell, 2011; McMichael, In Press), agricultural crop yields, as key determinants of childhood nutrition and development (Schlenker and Roberts, 2009; Lobell *et al*., 2011), and infectious diseases (Altizer *et al*., 2006), for example. These are briefly elaborated here.

[INSERT FIGURE 11-7 HERE
Figure 11-7: Extreme warming by 2100 from RCP8.5. Mean temperatures above levels around 2000. Note higher effects over land. Source: WGI AR5 _____.]

11.8.1. Exceeding Adaptation Limits in High-End Warming Scenarios

The prospect of rapid and extreme levels of warming raises questions about the biological limitations to human adaptability. As discussed above, when the surrounding environment exceeds body temperature at high humidity, the body has limited capacity to lose excess heat, and over time the core temperature will rise with, eventually, fatal consequence.

Sherwood and Huber (2010) argue that humans cannot tolerate sustained periods of wet-bulb temperatures above 35°C. They conclude that a global mean warming of roughly 7°C above current temperatures would create small land areas where metabolic heat dissipation would become impossible. An increase of 11-12°C would enlarge these zones to encompass most of today's human population. While transformative adaptation measures such as underground settlements or "bubble cities" might make such conditions habitable for humans, present ways of life would become impossible.

Working conditions are hazardous at lower thresholds. The U.S. military, for example, suspends all physical training and strenuous exercise when the wet bulb globe temperature (WBGT) exceeds 32°C (Willett and Sherwood, 2012) while international labor standards suggest the time acclimatized individuals spend doing low intensity labor such as office work be halved under such conditions (Kjellstrom *et al*., 2009a). (WBGT is a heat index closely related to the wet-bulb temperature that also incorporates measures of radiant heat from the sun and evaporative cooling due to

wind.) Assuming no adaptation and a transition in the labor force from agricultural to more service and industrial occupations, Kjellstrom *et al*. (2009b) estimate that global mean warming of 3.4°C above preindustrial temperatures will lead to losses in labor productivity of 11-27% in Andean and Central America, Southeast Asia and the Caribbean. Dunne *et al*. (2013) estimate losses to global labor productivity under a similar degree of warming in an analysis that fixes the population distribution to that of 2010 and does not consider changes in the labor force. They estimate that, under the RCP 8.5 scenario in which carbon dioxide concentrations continue to rise through 2200, global labor productivity will be reduced during the hottest months to 60% in 2100 and less than 40% in 2200.

Maloney and Forbes (Maloney and Forbes, 2011) use two heat balance models to examine the potential constraints heat will place on human activity in Perth, Australia in 2070. The authors consider a business-as-usual emissions scenario in which mean *regional* temperature increases by 6°C and assume temperature variability, relative humidity and wind speed mirror current conditions. They estimate that the number of days when heat balance will not be possible while undertaking moderate activity is estimated to increase from less than one to 11-23 days per year for acclimatized individuals, and from 13-14 to 56-60 days per year for unacclimatized individuals (ranges reflect the estimates derived from the two models). Heat stroke, an uncontrolled rise in core body temperature, would ensue in less than two hours for those performing physical labor on 15-26 days out of the year for acclimatized and 67-68 days out of the year for unacclimatized individuals, relative to 1-2 and 17-18 days out of the year at present.

Willett and Sherwood (2012) estimate future changes in summertime WBGT across 15 geographic regions. With regional warming of 5°C and assuming constant relative humidity, extreme prolonged heat events during which the 5-day average maximum WBGT is 35°C or higher are predicted to occur for over 90% of the summer in India, Northern Australia, Southeastern USA and the Caribbean, compared to current rates between 20-35%. It is projected that tropical and mid-latitude regions will be particularly badly affected, even though they will be warming less than the global average, due to greater increases in absolute humidity. Although the authors do not attempt to model the health impacts of such prolonged extreme heat, unprotected outdoor labor during the daytime in these conditions would be perilous for most of the summer.

11.8.2. Agricultural Limitations and Human Nutrition

Agricultural crops similarly have physiological limitations in terms of thermal and water stress. Analysis of six decades of late-spring barley yields in the Czech Republic show a strong and symmetrical inverted U-shaped relationship to rainfall and to temperature (Brázdil *et al*., 2009). Beyond the climate tolerance range, yields decline rapidly with too much or too little heat or soil moisture. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures are essentially linear (Lloyd *et al*., 2011; Lake *et al*., 2012), reflecting uncertainties about non-linear parameter values, future extreme events and climatic thresholds for other influences such as infestations and plant diseases.

Experimental field studies by the International Rice Research Institute have estimated that rice yields decline by about 10% for each 1°C rise in overnight temperature during flowering (Peng *et al*., 2004). Rice seed set is impaired at air temperatures above about 35°C (Yoshida *et al*., 1981), although there is the potential to breed more heat tolerant cultivars (Matsui *et al*., 2001; Jagadish *et al*., 2010). Corn fails to germinate at about 40°C (Blacklow, 1972; Birch *et al*., 1998). The lethal temperature for wheat appears to be about 47.5°C, while key phenological stages such as sowing to emergence and grain-filling have lower maximum temperature thresholds of 32.7°C and 35.4°C, respectively (Porter and Gawith, 1999; Porter and Semenov, 2005). For more information see Chapter 7, and recent reviews such as Texeira et al. (Teixeira *et al*., 2011). Water insufficiency is likely to constrain agriculture under extreme warming in some regions. For example, failures of rain-fed crops due to lack of available water are predicted to occur once every two years in much of southern Africa with a 5°C global average temperature increase (Thornton *et al*., 2011).

11.8.3. Infectious Disease Patterns under Extreme Warming

Substantial warming (above the global average) in higher-latitude regions will open up new terrain for some infectious diseases that are limited at present by low temperature boundaries. The northwards extensions in Canada and Scandinavia of tick populations, the vectors for Lyme disease and tick-borne encephalitis respectively, provide a foretaste of how this can happen (Lindgren and Gustafson, 2001; Ogden *et al*., 2006).

On the other hand, the emergence of new temperature regimes that exceed optimal conditions for vector and host species will reduce the potential for infectious disease transmission and, with high enough temperature rise, may eventually eliminate some infectious diseases that exist at present close to their upper tolerable temperature limits. For example, adults of two malaria-transmitting mosquito species are unable to survive temperatures much above 40°C in laboratory experiments (Lyons *et al*., 2012), although in the external world they may seek out tolerable microclimates. Reproduction of the malaria parasite within the mosquito is impaired at lesser raised temperatures (Paaijmans *et al*., 2009). Larval development of *Aedes albopictus,* an Asian mosquito vector of dengue and chikungunya, also does not occur at or above 40°C (Delatte *et al*., 2009).

11.8.4. Health Consequences of Displacement, Migration, and Social Conflict

More human migration can be expected under extreme levels of warming as adaptive capacity becomes overwhelmed by the impacts of climate change in more regions. Gemenne (2011) argues that the most significant difference between the nature of human migration in response to 4°C of warming relative to 2°C would be to remove many people's ability to choose whether to stay or leave when confronted with environmental changes. Health studies of refugees, migrants, and people in resettlement schemes suggests that forced displacement, in turn, is likely to lead to more adverse health impacts than voluntary migration or planned resettlement (McMichael *et al*., 2012).

Water scarcity is predicted to increase as a result of climate change in large portions of Africa, South Asia and the Americas (Fung *et al*., 2011). Modeling by Fung *et al*. (2011) suggests that while population growth will be the primary determinant of water scarcity in a +2°C world, in a +4°C scenario climate change will become the more important driver. It is prudent to assume such climate-induced water scarcity will lead to social and geopolitical tensions that may result in conflict, violence and displacement.

11.8.5. Reliance on Infrastructure

Under severe climate regimes, societies may be able to protect themselves with an increases prevalence of enclosed living and working environments, first for their most vulnerable members: the young, old, ill, and manual laborers. Reliance on the needed infrastructure, however, also entails increased vulnerability to unreliability of electricity and water supplies. What once was an inconvenience can become a serious health hazard if many people rely on such protection (Anderson and Bell, 2012).

11.9. Co-Benefits

Essentially every human activity affects (and is affected by) climate and health status in some way, but not all are strongly linked to either and even fewer strongly to both. Here we focus on the latter, i.e., measures to mitigate the atmospheric concentration of warming CAPs (climate altering pollutants) that also hold the potential to significantly benefit human health (Haines *et al*., 2007; Apsimon *et al*., 2009; Smith and Balakrishnan, 2009; UNEP, 2011; Shindell *et al*., 2012).The literature on health co-benefits associated with climate change mitigation strategies falls into five categories (Smith *et al*., 2009; Smith and Balakrishnan, 2009): Those that also (1) Reduce emissions of health-damaging pollutants, either primary or precursors to other pollutants; (2) Increase access to reproductive health services; (3) Decrease ruminant meat consumption; (4) Increase active transport from modifications to the built environment; (5) Increase in urban green-space. In addition, there are side effects of mitigation measures, such

as geoengineering, for example, that are potentially deleterious for human health, and these are addressed in WGIII, chapter x. In Table 11-4, we summarize what is known about the five categories, and below provide some additional detail for the first two.

[INSERT TABLE 11-4 HERE
Table 11-4: Summary of recent research on co-benefits of climate change mitigation. See text for details on the first two categories.]

11.9.1. Reduction of Co-Pollutants

Most of the publications related to CAPs and health-damaging pollutants refer to fuel combustion and fall into two major categories: 1) improvement in energy efficiency will reduce emissions of CO_2 and health-damaging pollutants if the energy is derived from combustion of fossil fuels or non-renewable biomass fuels, either directly or through the electric power system; in addition, 2) increases of combustion efficiency (decreasing emission of incomplete combustion products) will have both climate and health benefits, even if there is no change in energy efficiency and/or fuel itself is renewable, i.e. carbon neutral. This is because a number of the products of incomplete combustion are climate altering and nearly all are damaging to health (Smith and Balakrishnan, 2009).

Studies of the health co-benefits of reduction in air pollutants include sources that produce outdoor air pollution (Bell *et al*., 2008a) and household sources (Po *et al*., 2011). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for a substantial percent of primary outdoor fine particle pollution as well, perhaps a sixth to a quarter in China and India, for example (Chafe *et al*., (Submitted)) indicating that reductions in emissions from household sources could yield co-benefits through the outdoor pollution pathway as well.

Another category of air pollution co-benefits comes from controls for methane emissions that both reduce radiative forcing and potentially reduces human exposures to ambient ozone, for which methane is a precursor.

11.9.1.1. Outdoor Sources

Primary co-pollutants, such as particulate matter (PM) and carbon monoxide (CO) are those released at the point of combustion, while secondary co-pollutants, such as tropospheric ozone and sulphate particles, are formed downwind from the combustion source via atmospheric chemical interactions (Jerrett *et al*., 2009). As noted in Section 11.2, outdoors, the production and distribution of some secondary co-pollutants is exacerbated by temperature-associated attributes of climate change itself, thus posing a positive feedback effect.

The burden of disease from outdoor exposures in a country may often be greater in populations with low socioeconomic status, both because of living in areas with higher exposures and because these populations often have worse health and are subjected to multiple additional negative environmental and social exposures (Morello-Frosch *et al*., 2011).

11.9.1.2. Household Sources

Globally, the largest exposures from the pollutants from poor fuel combustion occur in the poorest populations. This is because household use of biomass for cooking is distributed nearly inversely with income. Essentially, no poor family can afford gas or electricity for cooking and very few families who can afford to do so, do not. Thus, the approximate 41% of all world households using solid fuels for cooking are all among the poor in developing countries (Bonjour *et al*., forthcoming in 2013).

11.9.1.3. Primary Co-Pollutants

Outdoor exposure to PM, especially to particles with diameters less than 2.5 μm ($PM_{2.5}$), contributes significantly to ill-health including cardio- and cerebrovascular disease, chronic and acute respiratory illnesses, lung cancer, and possibly other diseases. The Comparative Risk Assessment (CRA) for outdoor air pollution done as part of the Global Burden of Disease (GBD) 2010 Project found approximately 3.2 million premature deaths globally from ambient particle pollution or about 3% of the global burden of disease (Lim *et al.*, 2012). Importantly, reductions in ambient PM concentrations have also been shown to decrease morbidity and premature mortality (Boldo *et al.*, 2010). A significant portion of ambient particle pollution derives from fuel combustion, perhaps 80% globally (GEA, 2012).

Because of higher exposures, an additional set of diseases has been associated with combustion products in households burning biomass and/or coal for cooking and heating. Thus, in addition to the diseases noted above, cataracts, low birth weight, and stillbirth have been associated strongly with exposures to incomplete combustion products, such as PM and CO. CO has impacts on unborn children in utero through exposures to their pregnant mothers (World Health Organization Regional Office for Europe, 2010). There is also growing evidence of exacerbation of tuberculosis (Pokhrel *et al.*, 2010) in adults and cognitive effects in children (Dix-Cooper *et al.*, 2012). The CRA of the GBD-2010 found 3.5 million premature deaths annually from household air pollution derived from cooking fuels or 4.4% of the global burden of disease (Lim *et al.*, 2012). Importantly, there are also studies showing health benefits of household interventions, including child pneumonia (Smith *et al.*, 2011), blood pressure (McCracken *et al.*, 2007; Baumgartner *et al.*, 2011), lung cancer (Lan *et al.*, 2002), and chronic obstructive pulmonary disease (Chapman *et al.*, 2005). Another half a million premature deaths are attributed to household cookfuel's contribution to outdoor air pollution, making a total of about 4 million in 2010 or 4.9% of the global burden of disease (Lim *et al.*, 2012).

Black carbon (BC), a primary product of incomplete combustion, is both a strong CAP and health-damaging (IPCC, 2007; Ramanathan and Carmichael, 2008; Bond *et al.*, 2013). A systematic review, meta-analysis, and the largest cohort study to date of the health effects of BC found that there were probably stronger effects on mortality from exposure to BC than for undifferentiated fine particles ($PM_{2.5}$) (Smith *et al.*, 2009). The conclusion is that BC abatement represents an opportunity to achieve both climate mitigation and health benefits, a conclusion shared by other recent reviews as well (UNEP, 2011).

Other co-pollutants with CO_2 from fuel use are carbon monoxide, non-methane hydrocarbons, and sulfur and nitrogen oxides. Each of these poses risks as well as being climate altering in different ways. See WGI for their climate potential and WHO reviews of health impacts (World Health Organization Regional Office for Europe, 2010)(WHO, 2006).

11.9.1.4. Secondary Co-Pollutants

In addition to being a strong CAP, methane (CH_4) is also a significant precursor to regional anthropogenic tropospheric ozone production, which itself is a CAP. Thus, reductions in CH_4 could lead to reductions in ambient tropospheric ozone concentrations, which in turn could result in reductions in population morbidity and premature mortality and climate forcing.

One study found that a reduction of global anthropogenic CH_4 emissions by 20% beginning in 2010 could decrease the average daily maximum 8-h surface ozone by 1 ppb by volume, globally; sufficient to prevent 30,000 premature all-cause mortalities globally in 2030, and 370,000 between 2010 and 2030. (West *et al.*, 2006) CH_4 emissions are generally accepted as the primary anthropogenic source of tropospheric ozone concentrations above other human-caused emissions of ozone precursors (West *et al.*, 2007) and thus, the indirect health co-benefits of CH_4 reductions are epidemiologically significant. On the other hand, the CRA of the GBD-2010 estimated 150,000 premature deaths from all ozone exposures globally in 2010, indicating a more conservative interpretation of the evidence for mortality from ozone (Lim *et al.*, 2012).

In an analysis of ozone trends from 1998-2008 in the United States, Lefohn et al. (Lefohn *et al.*, 2010) found that 1-hour and 8-hour ambient ozone averages have either decreased or failed to increase due to successful regulations of ozone precursors, predominantly NO_x and CH_4 (Lefohn *et al.*, 2010). This is consistent with the US EPA (US EPA, 2010) conclusion that in the US, for the period 1980-2008, emissions of nitrogen oxides and volatile organic compounds fell by 40% and 47%, respectively (US EPA, 2010; Lefohn *et al.*, 2010). These results point to the effectiveness of reducing ambient ozone concentrations through regulatory tools that reduce the emissions of ozone precursors, some of which, like CH_4, are GHGs.

Not every CAP emitted from fuel combustion is warming. The most prominent example is sulfur dioxide emitted from fossil fuel combustion, which changes to particle sulfate in the atmosphere. Although health damaging, sulfate particle have a cooling effect on global radiative forcing. Thus, reduction of sulfur emissions, which is important for health protection, does not qualify as a co-benefit activity since it actually acts to unmask more of the warming effect of other CAP emissions (Smith *et al.*, 2009). See also WGI, Ch. x.

11.9.1.5. Case Studies of Co-Benefits of Air Pollution Reductions

A recent UNEP- and WMO-led study of black carbon and tropospheric ozone found that, if all of 400 proposed BC and CH_4 mitigation measures were implemented on a global scale, the estimated benefits to health would come predominately from reducing $PM_{2.5}$ (0.7 – 4.6 million avoided premature deaths; 5.3 – 37.4 million avoided years of life lost) compared to tropospheric ozone (0.04 – 0.52 million avoided premature deaths; 0.35 – 4.7 million avoided years of life lost) based on 2030 population figures (UNEP, 2011). About 98% of the avoided deaths would come from reducing $PM_{2.5}$, with 80% of the estimated health benefits occurring in Asia (Anenberg *et al.*, 2012).

A study of the benefits of a hypothetical 10-year program to introduce advanced combustion cookstoves in India found that in addition to reducing premature mortality by about 2 million and DALYs by 55 million over that period, there would be reduction of 0.5-1.0 billion tons CO_2-eq (Wilkinson *et al.*, 2009).

In their estimation of effects of hypothetical physical and behavioral modifications in UK housing, Wilkinson and colleagues (Wilkinson *et al.*, 2009) found that the magnitude and direction of implications for health depended heavily on the details of the intervention. However, the interventions were found to be generally positive for health. In a strategy of housing modification that included combined fabric, ventilation, and fuel switching, along with behavioral changes, it was estimated that 850 fewer DALYs, and a savings of 0.6 megatonnes of CO_2 per million population in one year could be achieved. These calculations were made by comparing the health of the 2010 population with and without the specified physical and behavioral modifications (Wilkinson *et al.*, 2009).

Markandya *et al.* (2009) assessed the changes in emissions of $PM_{2.5}$ and subsequent effects on population health that could result from climate change mitigation measures aimed to reduce GHG emissions by 50% by 2050 (compared with 1990 emissions) from the electricity generation sector in the EU, China, and India (Markandya *et al.*, 2009). In all three regions, changes in modes of production of electricity to reduce CO_2 emissions were found to reduce $PM_{2.5}$ and associated mortality. The greatest effect was found in India and the smallest in the EU. The analysis also found that health benefits greatly offset the cost of GHG emission reductions, especially in the Indian context where emissions are high but costs of implementing the measures are low (Markandya *et al.*, 2009).

11.9.2. Access to Reproductive Health Services

Population growth is another factor involved in the consumption of resources and emissions of CAPs. Although population growth rates and total population size do not alone determine emissions (WG1), population size is an important factor. One study showed that CO_2 emissions could be lower by 30% by 2100 if access to contraception was provided to those women expressing a need for it (O'Neill *et al.*, 2010). Providing the unmet need for these services in aresa such as the Sahel region of Africa with both high fertility and high vulnerabity to climate change can potentially significantly reduce human suffering as climate change proceeds (Potts and Henderson, 2012). This is important not only in poor countries, however, but also rich ones like the US, where there is unmet need for

services as well as high CO_2 emissions per capita. Slowing population growth through lowering fertility, as might be achieved by increasing access to family planning has been associated with improved maternal and child health in two main ways: increased birth spacing and reducing births by very young and old mothers.

11.9.2.1. Birth and Pregnancy Intervals

Current evidence supports, with medium confidence, that short birth intervals (defined as birth intervals between <19 and <25 months and inter-pregnancy intervals <6 months) are associated with increased risks of uterine rupture and bleeding (placental abruption and placenta previa) (Bujold *et al*., 2002; Conde-Agudelo *et al*., 2007). There is also a correlation between short birth interval and elevated risk of low-birth-weight: Zhu et al. (Zhu, 2005) found, in a review of three studies performed in the United States that a J-shaped relationship existed between inter-pregnancy spacing in that the lowest risk of adverse birth outcomes (i.e., low birth weight, existed between 18-23 months and risk increased as it departed, in either direction (Zhu, 2005).

Although an ecological analysis, a review across 17 countries shows a strikingly coherent picture of the relationship between birth spacing (as preceding birth intervals), malnutrition, and reductions in child, infant and neonatal mortality (Figure 11-8) with risk of child malnutrition and mortality both increasing with shorter birth intervals (Rutstein, 2005). One study estimated that shifting birth spacing from current patterns in the world to a minimum of 24 months would reduce by 20% (~2 million) the current excess child mortality in the world (Rutstein, 2005; Gribble *et al*., 2009).

[INSERT FIGURE 11-8 HERE
Figure 11-8: Reduction in child (under 5 years) mortality due to increasing spacing of birth (Previous Birth Interval) based on studies in 17 countries. Source: Rutstein (2005).]

11.9.2.2. Maternal Age at Birth

Risk of death during delivery is highest in very young and very old mothers, which are also the age groups most wishing to control their fertility (Engelman, 2010). Women who begin child bearing under the age of 20 years are at an increased risk of developing pregnancy complications such as cephalopelvic disproportion, obstructed labor, preterm delivery, toxemia, bleeding, and maternal death (Tsui *et al*., 2007). Additionally, children born to women under the age of 20 are at increased risk of fetal growth retardation and low birth weight, which can both lead to long term physical and mental developmental problems (Tsui *et al*., 2007). Childbearing at later ages (>35 years) is associated with increased risks for the child of miscarriage, perinatal mortality, preterm birth, low birth weight, congenital and chromosomal abnormalities, and increased risks for the mother of placental previa, gestational diabetes, cesarean delivery and maternal death (Cleary-Goldman *et al*., 2005; Ujah *et al*., 2005).

Thus, providing access to family planning saves women's lives by reducing the total number of births and, in particular, through the reduction of births in high-risk groups (Prata, 2009). Studies have found that when women have access to family planning, it is the highest risk age groups (youngest and oldest women) who reduce their fertility most, in other words, family planning has a differential impact on maternal mortality reduction through reducing births in the highest risk groups (Diamond-Smith and Potts, 2011).

11.10. Conclusions

11.10.1. It is certain that a range of human diseases are sensitive to climate conditions, but the health impacts of these diseases are also affected by many other changing factors, making it currently difficult to quantify precisely the influence of climate change itself on present-day patterns of disease globally.

11.10.2. Much reduction of health impacts from climate change can be avoided through provision of basic health improvements to world's poor populations.

11.10.3. Much additional reduction can come from targeted adaptation efforts, such as early warning systems and good disaster management.

11.10.4. The world is not progressing rapidly with these advances, however, leading to a likely increasing net health impact from climate change in next decades.

11.10.5. There are residual health impacts that cannot be handled through adaptation in any reasonable way particularly if climate change proceeds to extreme conditions.

11.10.6. Well-chosen adaptation and mitigation measures may achieve substantial health gains (co-benefits), in the short- to medium-term.

11.11. Key Uncertainties and Research Recommendations

The key uncertainty for estimating health impacts from climate change over the next few decades is the extent that society will provide basic public health services, disaster warning and response systems, and poverty alleviation throughout the world. With a strong response, climate change health effects will be relatively small, but otherwise climate-attributable cases of disease and injury will steadily increase. Research is needed into exactly how interventions should be implemented to optimally improve health in the short-term, and lower the health threat of climate change. Another question that warrants attention is the best ways to motivate local, national, and international actions to greatly reduce servere poverty, and improve health services and disaster warning/response systems. More work needs to be done as well to evaluate the effects and costs of health adaptation policies and interventions.

There is a lack of robust analytical methods to untangle complex climate–health relationships such as the effect of more extreme weather on water and sanitation provision and diarrhoea rates (WHO/DFID, 2010). Risk assessment frameworks are needed that not only make the best use of traditional epidemiologic methods but also take into account the specific characteristics of climate change. These include the long-term and uncertain nature of the exposure and the effects on multiple physical and biotic systems that have the potential for diverse and widespread effects, including high-impact events.

In the longer term, there are plausible scenarios for rather extreme climate regimes by the end of the century or before, on pathways that are committed to even more extreme climates in the following century. It is difficult to do research directly on the effect of conditions that do not exist yet at any scale. Nevertheless, trying to understand the health impacts of these lower probability but severe future climates that could potentially affect the lives of nearly every baby born from today onwards given global life expectancies should have high priority. This understanding can help society understand how valuable actions today are to both mitigate and be ready for such conditions.

Frequently Asked Questions

FAQ 11.1: How is climate change thought to affect human health?
There are three major routes by which climate change is thought to affect health 1) by direct impacts, such as heat stress and floods; 2) by indirect impacts mediated through the natural environment, such as shifts in patterns of disease-carrying mosquitoes and waterborne diseases; and 3) indirect impacts mediated through societal systems, such as damage to health care systems by extreme weather events, malnutrition and mental illness from altered agricultural production, and stress and malnutrition from population displacement due to sea-level rise.

FAQ 11.2: Will climate change have benefits for health?
Yes, some populations in temperate areas may be at less risk from extreme cold and some populations may benefit from greater agricultural productivity and lower levels of vector-borne disease, but the overall impact for nearly all populations and for the world as a whole is expected to be much more negative than beneficial.

FAQ 11.3: Who is most affected by climate change?

As climate change mainly acts to exacerbate existing disease patterns and for the next decades will not probably not create significant new ones, those populations already under stress from disease will be most affected. Thus, most assessments indicate that it is poor and disenfranchised groups everywhere that will bear the most risk and, globally, the greatest burden will fall on poor countries, particularly on poor children, who are most affected today by such climate-related diseases as malaria, malnutrition, and diarrhea.

FAQ 11.4: What is the most important adaptation strategy to reduce the health impacts of climate change?

Accelerating current public health and medical interventions directed toward reducing existing disease in the world, particularly for climate-related diseases in poor countries, is the single most important step that can be taken to reduce the health impacts of climate change. Reducing poverty is the next most important for health globally.

FAQ 11.5: What are health "co-benefits" of climate change mitigation measures?

A number of mitigation measures to reduce emissions of climate-altering pollutants (CAPs) seem to have important direct health benefits in addition to reducing the risk of climate change, a relationship called "co-benefits." For example, increasing energy efficiency reduces health-damaging air pollution from fuel combustion; reducing ruminant meat consumption in many populations reduces both CAPs and the risk of chronic disease such as cancer; increasing the opportunities and attractiveness of active transport (walking and cycling) in place of travel by motor vehicle reduces air pollution and improves health directly; and providing access to reproductive health services slows population and energy demand growth and reduces risks of child and maternal mortality.

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Table 11-1: Vector-borne diseases.

Disease	Population at risk millions (m) / billions (b)			Climate Sensitivity[1] and Confidence in Climate Effect: increased(>) or decreased (<)temperature(T) rainfall(R) humidity(H); increased cases(+) decreased cases (-)both reported (±); high confidence in global effect - **Bold,** high confidence in local effect -*italic*, low confidence in effect - roman		Key References
	Area	Cases^{-yr}	At risk			
Malaria	Mainly Africa, SE Asia,	247m	3.3b	>$T^{2,3}$ + - ± >$R^{2,3}$ + -	<R >$H^{2,3}$ -	WHO 2008, Kelly-Hope *et* al 2009, Omumbo *et al* 2011, Alonso *et al* 2011.
Dengue	100 countries esp Asia Pacific	50-100m	2.5b	**>T+ <T- >R +**	**<R- >H^3+ -**	Beebe 2009, Descloux 2012; Earnest *et al* 2012, Pham *et al* 2011. Kovat et al. 2013
Tick-borne diseases						
T-b encephalitis	Europe, Russian Fed Mongolia China	10,000-12,000		S^3		Tokarevich *et al* 2011
Lyme	Temperate areas of Europe, Asia N.America	≤23000 in USA		>T^3+ >H^3+		Bennet 2006, Ogden *et al* 2008,
Other vector-borne diseases						
Hemorrhagic fever (HFRS)	Global	0.15 – 0.2m		T+ R+	H+	Fang *et al* 2010
Plague	Endemic in natural foci globally			T+ >R^3+±	<R^3+	Stenseth *et al* 2006, Xu *et al* 2011
Other infectious diseases						
Nosocomial infections	All Hospitals			T+ H+		Perencevich *et al* 2008
Influenza	Global			>T^3+ <T^3+	R^3 >H^3 +-	Soebiyanto *et al* 2010, Tamerius *et al* 2011
Rotavirus	Global	0.45m		>$T^{3,4}$-,± >R -	>H-	Patel *et al* 2012, Pitzer *et al* 2011
Tuberculosis	Global	1.7m	100-200m	>R^3 +		Ane-Anyangwe *et al* 2006, Naranbat *et al* 2009;

[1] All diseases included show some seasonality of occurrence
S – no specific climate drivers reported
[2]Effects are *Anopheles* spp
[3] Location specific
[4] Seasonal peaks changed following vaccination

Table 11-2: Projected future health impacts of climate change through air pollution.

Location	Health impact	Models used		Climate scenario	Key assumptions	Outcome	Reference
United States	Ozone-related morbidity and mortality	Multipollutant, multiscale air quality from Community Multiscale Air Quality (CMAQ) Modeling System	GISS-GCM driven by A1B SRES emissions scenario for the period 1950-2055 and downscaled to a 36-km resolution using Mesoscale Meteorological model version 5 (MM5)	Global temperature increase of 1.59°C in 2050, compared to 1990s	Population held constant at 2000 levels	Climate change-driven air quality-related health effects will adversely affect greater than 2/3 of the continental U.S	Potential Impact of Climate Change on Air Pollution-Related Human Health Effects (Tagaris et al. 2009)
	$PM_{2.5}$-related morbidity and mortality	Meteorological data from Goddard Institute for Space Studies (GISS) Global Climate Model (GCM)			Mortality rates held constant at 2000 levels	Approximately 4000 additional annual premature deaths due to climate change impacts on $PM_{2.5}$ compared to 300 due to climate change-induced ozone changes	
		Penn State/NCAR Meso scale Model (MM5 model) used to downscale GISS-GCM outputs to a regional scale			Disease incidence rates held constant at 2000 levels	$PM_{2.5}$ and ozone-related health impacts vary spatially	
		Health effect analysis conducted using U.S. EPA's Environmental Benefits Mapping and Analysis Program (BenMAP)				Increased premature mortality due to elevated ozone concentrations will be offset by lower mortality from reductions in $PM_{2.5}$ in 11 states	
South-central Canada (Montreal, Ottawa, Toronto, Windsor)	air pollution mortality	GCM	GCM downscaled using regression-based statistical method for the periods 2040-2059 and 2070-2089	Air temperature from SRES A2 and B2 scenarios	Population and age structure not directly taken into account	Air pollution-related mortality could increase about 20–30% by the 2050s and 30–45% by the 2080s, projected with climate change	Differential and combined impacts of extreme temperatures and air pollution on human mortality in south-central Canada. Part II: future estimates (Cheng et al. 2008)
						Increase in air pollution-related mortality would be largely driven by increases in ozone effects	
Africa, Middle East, South Asia, Southeast Asia, East Asia, Japan and Australia, Former Soviet Union, Europe, North America, Latin America	Premature ozone-related mortality	GCM	GCM and LMDz-INCA models driven by SRES A2 emissions scenario for 2030	Baseline simulation from 2000	World population of 9.17 billion by 2030	Under current legislation (CLE) scenario, estimated reduction in premature ozone-related human mortalities by 190,000 globally in 2030, mostly in Africa	Human mortality effects of future concentrations of tropospheric ozone (West et al. 2007)
		Laboratoire de Météorologie Dynamique (LMDz)-Interaction Chimie - Aérosols (INCA) chemistry-climate model			Spatial distribution by region based on 2003 population from Landscan database	Under maximum feasible reduction (MFR) scenario, estimated reduction in premature ozone-related human mortalities by 460,000 in 2030, with the greatest reductions in South Asia	
					Constant baseline mortality rates through 2030		

Table 11-3: Number of malnourished children less than 5 years of age (in millions) in 2000 and under the NCAR climate model (using A2 scenario from AR4) till 2050. Assumptions for investment in agricultural productivity: + only in developing countries; ++ both in developing and developed countries. Results assume no CO_2 fertilization effects. Adapted from (Nelson *et al.*, 2009).

Scenario	South Asia	East Asia/ Pacific	Eu + Centr. Asia	LA & Carrib.	Middle East/ N.Africa	Sub2-Sah. Africa	Devel. Countr.
2000	75.6	23.8	4.1	7.7	3,5	32.7	147.9
2050							
No climate change	52.3	10.1	2.7	5.0	1.1	41.7	113.3
NCAR	59.1	14.5	3.7	6.4	2.1	52.2	138.5
NCAR + adaptation	54.2	10.1	3.0	4.9	1.4	44.1	118.9
NCAR ++adaptat'n	53.7	10.5	3.0	4.8	1.3	43.5	117.2

Table 11-4: Summary of recent research on co-benefits of climate change mitigation. See text for details on the first two categories.

Co-benefit category	**Benefits for health**	**Benefits for climate**	**Select publications since 2006**
Reduction of co-pollutants from outdoor and household sources	See text	See text	(Bell *et al*., 2008a)
			(Markandya, Armstrong et al. 2009)
			(Smith and Balakrishnan, 2009)
			(Smith, Jerrett et al. 2009)
			(Wilkinson *et al*., 2009)
			(Lefohn, Shadwick et al. 2010)
			(World Health Organization Regional Office for Europe 2010)
			(Po *et al*., 2011)
			(Anenberg *et al*., 2012)
			(Lim, Vos et al. 2012)
Greater access to reproductive health services	See text	See text	(Conde-Agudelo *et al*., 2007)
			(Tsui, Creanga et al. 2007)
			(Gribble, Murray et al. 2009)
			(Prata 2009)
			(O'Neill, Jackman et al. 2010)
			(Diamond-Smith, Potts 2011)
			(Potts and Henderson, 2012)
Increases in urban green space	Reduced temperatures and heat island effects; reduced noise; enhanced safety; psychological benefits; better self-perceived health status	Reduce air pollution; more carbon sequestration (through forests and soil)	(McMichael, Powles et al. 2007)
			(Mitchell and Popham, 2007)
			(Babey *et al*., 2008)
			(Friel, Dangour et al. 2009)
			(Maas *et al*., 2009)
			(van den Berg *et al*., 2010)
			(van Dillen *et al*., 2011)
Less ruminant (red) meat consumption	May reduce (ischaemic) heart disease, stroke, colorectal cancer, breast cancer and prevalence of overweight/obese individuals	Fewer CH_4 emissions	(Sinha, Cross et al. 2009)
			(Smith and Balakrishnan, 2009)
			(Jakszyn *et al*., 2011)
			(Pan, Sun et al. 2012)
			(Xu *et al*., 2012)
Increases in active transport from modifications to the built environment, including smart growth	Increased physical activity; reduced obesity; reduced chronic disease; improved mental health; reduced exposure to air pollution; increased local access to essential services, including food stores; enhanced safety	Reduce CAP emissions associated with vehicle transport; possible mitigation of emissions through sequestration	(Babey *et al*., 2007)
			(Reed and Ainsworth, 2007)
			(Kaczynski and Henderson, 2008)
			(Casagrande *et al*., 2009)
			(Rundle *et al*., 2009)
			(Woodcock *et al*., 2009)
			(Grabow *et al*., 2011)
			(Durand *et al*., 2011)
			(McCormack and Shiell, 2011)

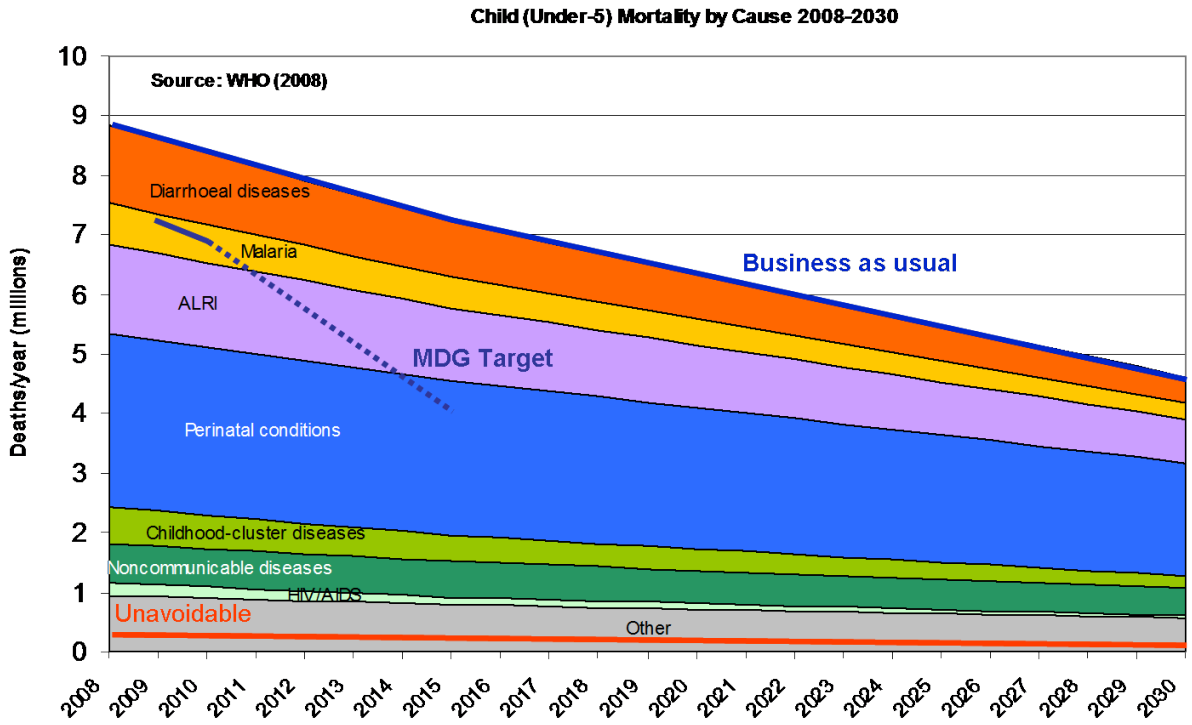


Figure 11-1: Climate change acts against human development: to reach the Millennium Development Goal for child mortality, the reduction in climate-sensitive causes of death at an early age must accelerate. Projected Child Mortality, 2008-2030, Including Climate-Sensitive Causes. ALRI is Acute Lower Respiratory Infections. Sources: Mortality projections by cause from WHO. Population projections from UN DESA. Child mortality rates from IGME. (Interagency Group for Child Mortality Estimation, 2011; United Nations, Department of Economic and Social Affairs, Population Division., 2011; World Health Organization, 2008).

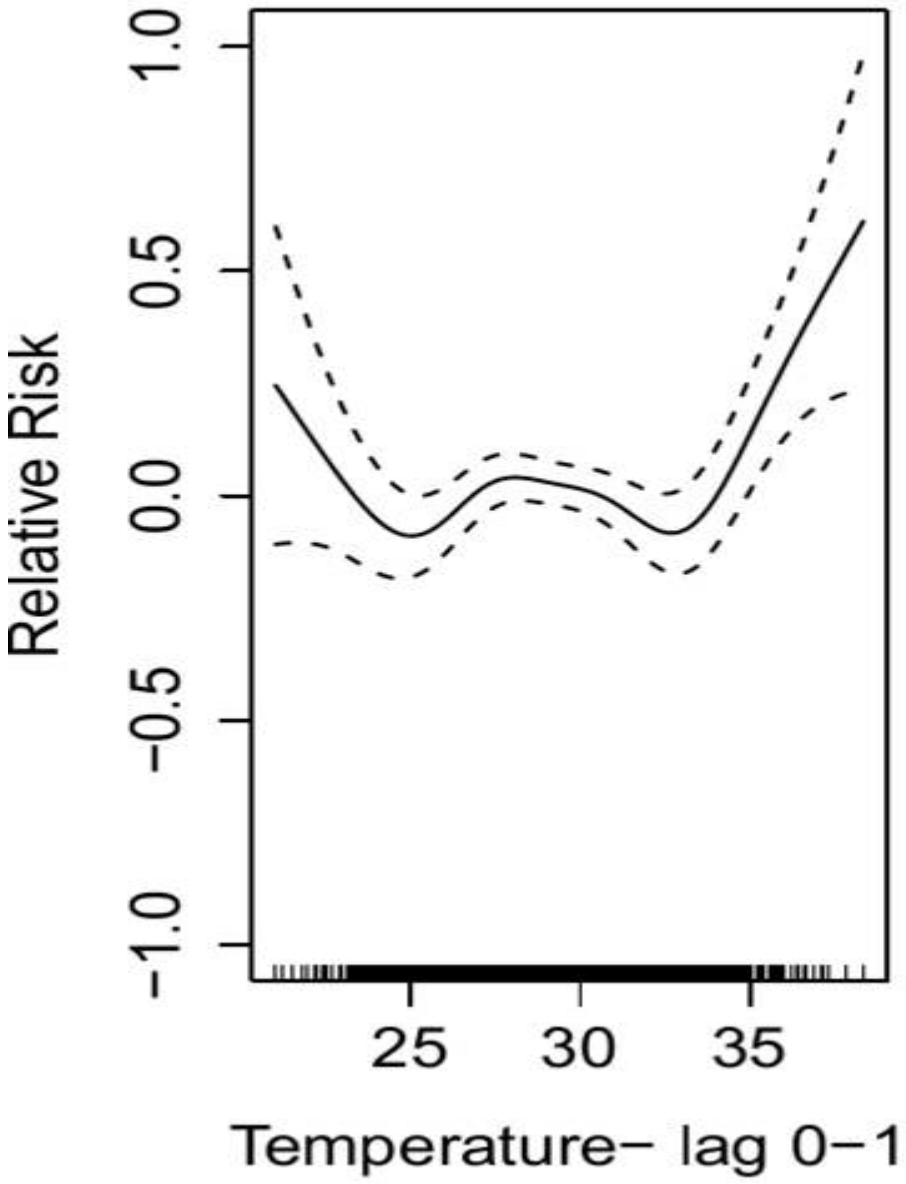
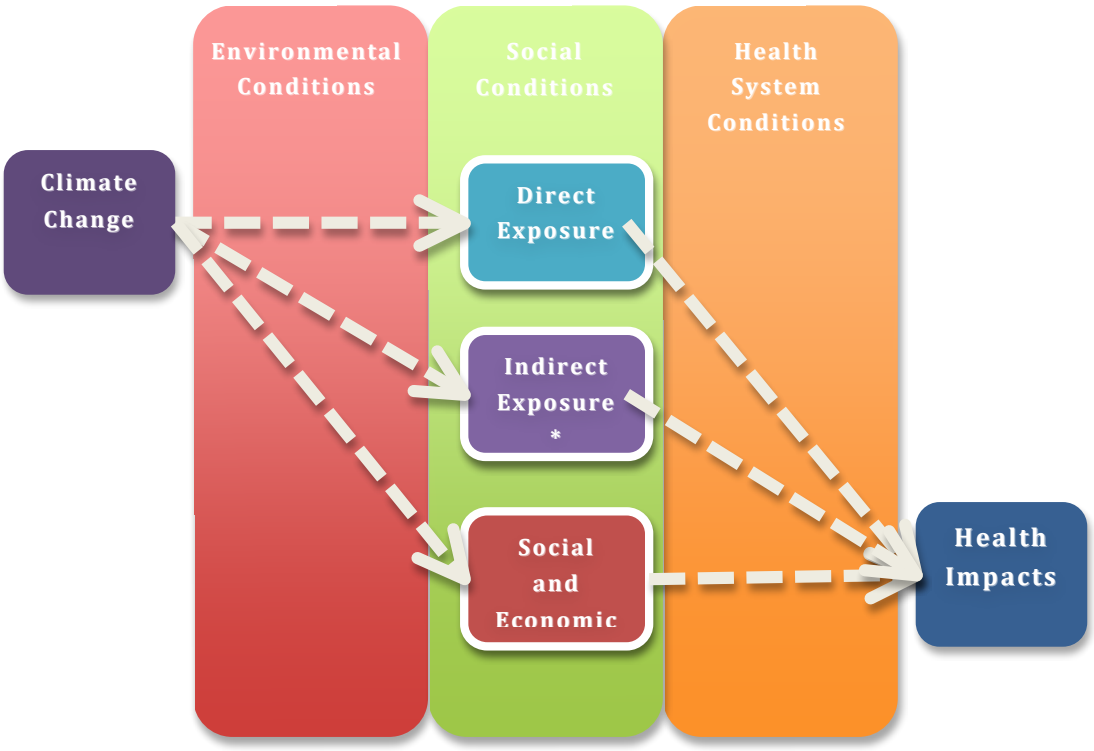


Figure 11-2: Relationship between the risk of dying and average temperature on the preceding day, persons aged over 60 years, Nouna, Burkina Faso. Y-axis: log(RR), X-axis: Temp in °C, lagged by one day. Dotted lines show 95% confidence limits. Source: Diboulo et al, 2012.



*Changes in water, air, food quality; vector ecology; ecosystems, agriculture, industry, and settlements
†Arrow inside 'condition' box indicates modifying influence

Figure 11-3: Ways in which climate, climate variability and climate change may influence human health. Source: E. Garcia (2011).

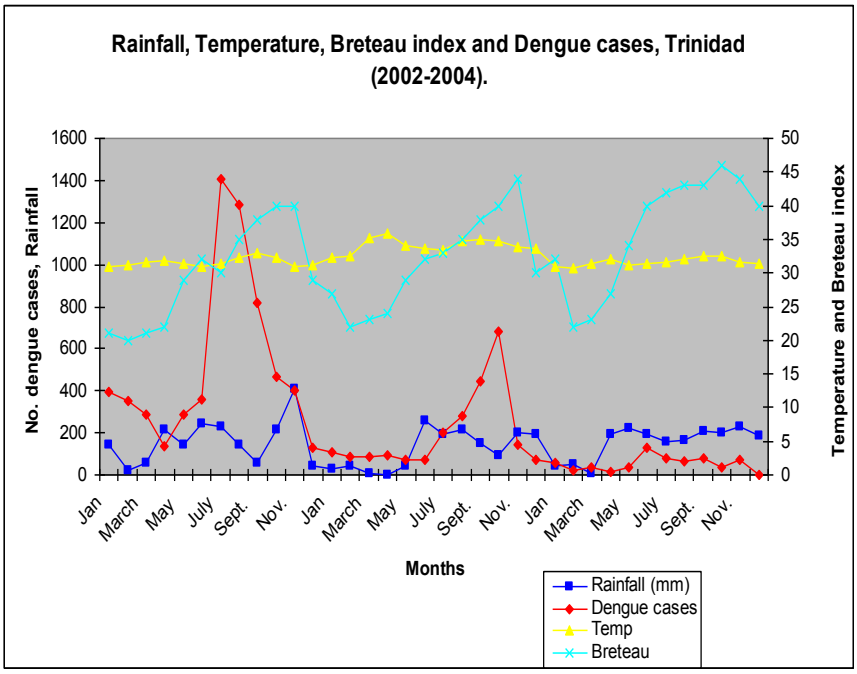


Figure 11-4: Rainfall, temperature, Breteau index (number of water containers with *A. aegypti* larvae per 100 houses), and dengue cases, Trinidad (2002-2004). Source: Chadee *et al.* (2007).

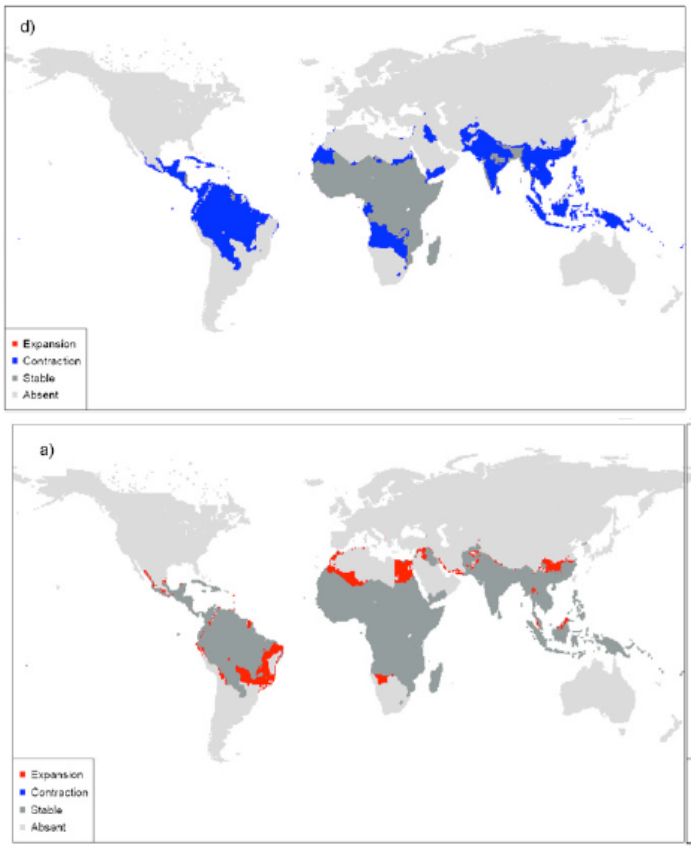


Figure 11-5: Contraction of the area of malaria transmission if economic development progresses as forecast (top panel, in blue); expansion in areas of transmission through higher temperatures (bottom panel, in red). Based on IPCC scenario A1B, projections to 2050. Source: Béguin *et al.* (2011).

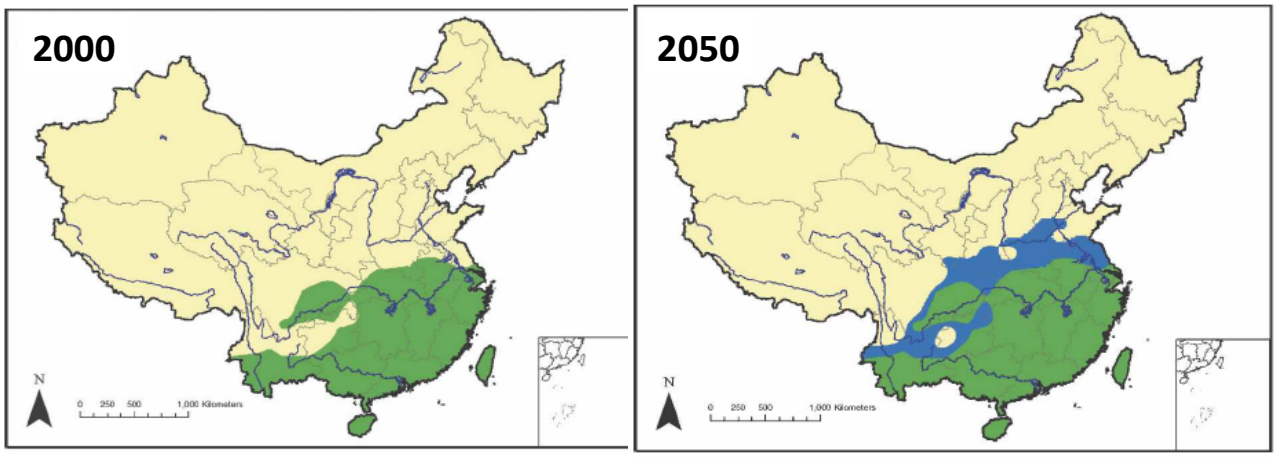


Figure 11-6: Projected risk map of schistosomiasis*(S. japonicum)* transmission in China in 2050. For comparison the current risk map in 2000. Green area denotes the range of schistosomiasis in 2000. The blue area shows the geographic expansion. Adapted from (Zhou *et al.*, 2008).

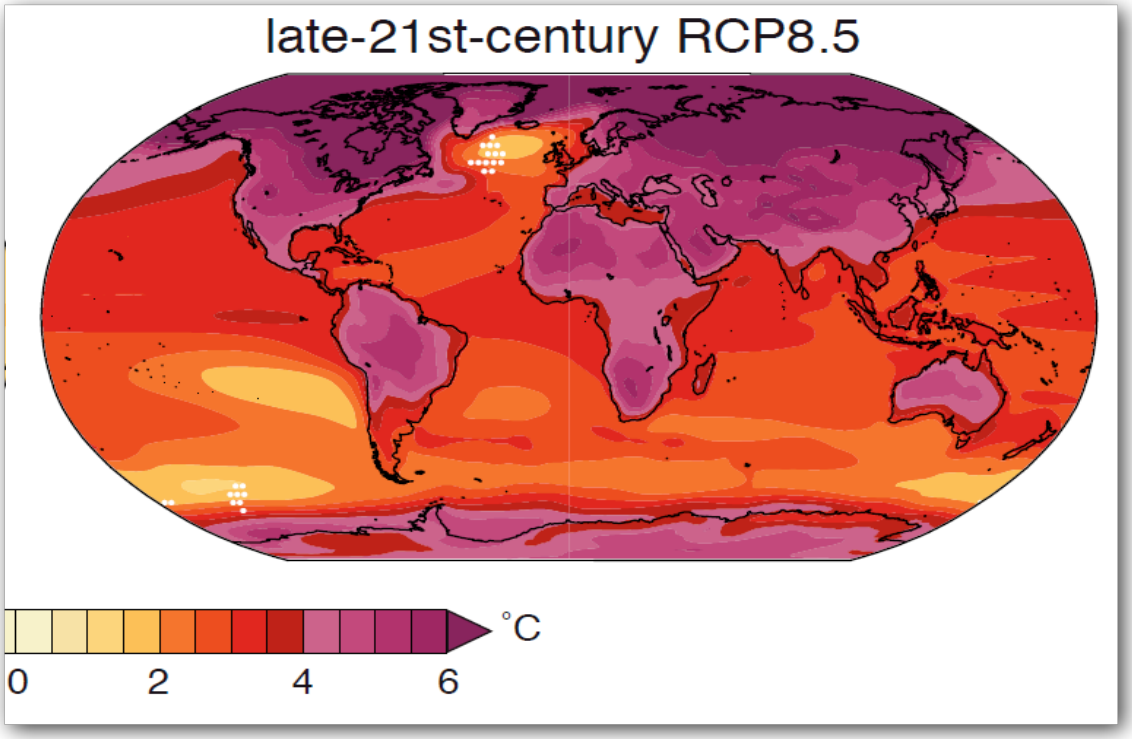


Figure 11-7: Extreme warming by 2100 from RCP8.5. Mean temperatures above levels around 2000. Note higher effects over land. Source: WGI AR5 _____.

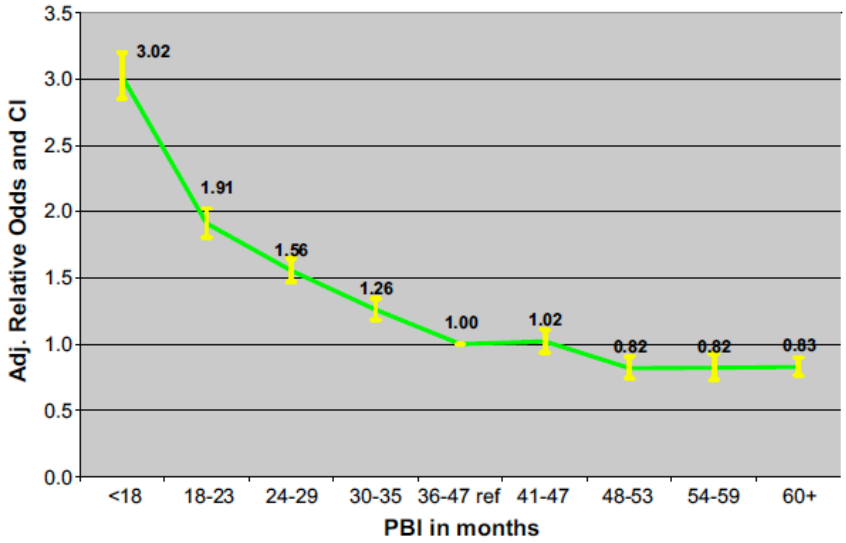


Figure 11-8: Reduction in child (under 5 years) mortality due to increasing spacing of birth (Previous Birth Interval) based on studies in 17 countries. Source: Rutstein (2005).

Chapter 12. Human Security

Coordinating Lead Authors
W. Neil Adger (UK), Juan Pulhin (Philippines)

Lead Authors
Jon Barnett (Australia), Geoff Dabelko (USA), Grete K. Hovelsrud (Norway), Marc Levy (USA), Úrsula Oswald-Spring (Mexico), Coleen Vogel (South Africa).

Contributing Authors
Helen Adams (UK), Jennifer Hodbod (UK), Stuart Kent (Australia), Marcela Tarazona (Colombia)

Review Editors
Paulina Aldunce (Chile), Robin Leichenko (USA)

Volunteer Chapter Scientist
Marcela Tarazona (Colombia)

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References

Executive Summary

Climate change threatens human security, because it a) undermines livelihoods, b) compromises culture and identity, c) increases migration that people would rather have avoided, and d) undermines the ability of states to provide the conditions necessary for human security (high agreement, robust evidence). Human security breakdowns almost never have single causes, but instead emerge from the interaction of multiple factors. For populations that are already socially marginalized, resource dependent, and have limited capital assets, human security will be progressively undermined as the climate changes [12.1.2; 12.2]. Increases in the rate and magnitude of climate change increase the risk to human security by exacerbating negative feedbacks between cultural processes, migration and violent conflict [12.7].

Climate change affects cultures and the cultural expressions important for maintaining identity and traditional and local forms of knowledge (medium evidence, high agreement) Climate change impacts will lead to significant changes in environmental and societal conditions throughout the natural world, and in human settlements. These changes will compromise dimensions of the cultural core and assets that are highly valued by societies [12.3]. The magnitude of the perceived loss depends on the robustness of cultural identity and the mechanisms for maintaining and transferring knowledge. Culture and local and traditional forms of knowledge are highly dynamic and context dependent, reflecting and reasserting values, and shaping both adaptive and maladaptive responses.

Traditional and indigenous forms of knowledge are a major resource for adapting to climate change except when the changes exceed the knowledge repertoire (high agreement, robust evidence). Indigenous peoples have adapted to highly variable and changing social and ecological conditions [12.3]. The current rate and magnitude of change will increasingly constrain the efficacy of indigenous and traditional knowledge in adaptive responses [12.3]. Currently many indigenous peoples are politically and economically marginalized and live in regions or depend on natural resources that are highly sensitive to climatic changes. Local and traditional knowledge are often neglected in policy and research, and mutual recognition and integration of local and traditional knowledge with scientific knowledge will increase the effectiveness of adaptation responses [12.3].

Climate change will have significant impacts on forms of migration that compromise human security (medium agreement, medium evidence). Some migration flows are sensitive to changes in resource availability and ecosystem services. Major extreme weather events have in the past led to significant population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. There is evidence that many vulnerable groups do not have the resources to be able to migrate to avoid the impacts of floods, storms and droughts. There is evidence from models, scenarios and observations that coastal inundation and loss of permafrost can lead to migration and resettlement [12.3.2, 12.4.2]. Migrants themselves may be vulnerable to climate change impacts in destination areas, particularly in urban centres in developing countries [12.4.2].

Mobility is a widely used and often effective strategy to maintain livelihoods in response to social and environmental changes (high agreement, medium evidence). There is robust evidence that migration and mobility are adaptation strategies in all regions of the world that experience climate variability. People that lack the ability to move will face higher exposure to weather-related extremes in both rural and urban areas in the developing world [12.4.3]. There is some evidence to suggest that expanding opportunities for mobility reduce vulnerability and

enhance human security. Observations of implementation of planned resettlement show that legitimate and inclusive planning processes help alleviate the conflict and insecurity that individuals and communities may experience.

Some of the factors that increase the risk of violent conflict including civil wars are sensitive to climate change (medium agreement, medium evidence). The evidence on the direct effect of climate change and variability on violence is contested. Though there is little agreement about causality, there is robust evidence that shows that low per capita incomes, economic contraction, and inconsistent state institutions are associated with the incidence of civil wars. These factors are sensitive to climate change. Climate change policy responses, particularly those associated with changing property rights to land, water and resources, can increase the risk of violent conflict. A range of policies and institutions at multiple scales has been demonstrated to reduce the effects of environmental change on the risk of violent conflict. Economic growth, high per capita incomes, strong democratic institutions, social protection during economic and climate shocks, and robust institutional structures that protect property rights and manage conflict all reduce the risk that climate variability and extremes will lead to violence.

People living in places affected by violent conflict are particularly vulnerable to climate change (high agreement, modest evidence). Evidence shows that large-scale violent conflict harms infrastructure, institutions, natural capital, social capital, and livelihood opportunities. Since these assets facilitate adaptation to climate change, there are strong grounds to infer that conflict drives vulnerability to climate change impacts [12.5.2].

Climate change will lead to new challenges to states and will shape both conditions of security and national security policies (medium agreement, medium evidence). Physical aspects of climate change, such as sea level rise, extreme events, and hydrologic disruptions, pose major challenges to vital transportation, water, and energy infrastructure [12.6]. Some states are experiencing major challenges to their territorial integrity, including Arctic countries, small island states, and other states highly vulnerable to sea level rise [12.5.4]. Some impacts of climate change, such as changes in sea ice, transboundary and shared water resources, and the migration of pelagic fish stocks, have the potential to increase rivalry among states. There is evidence that the presence of robust institutions can manage many of these rivalries such that human security is not severely eroded [12.6]. These threats to national security will affect the capacity of states and communities to provide human security.

12.1. Concepts and Evidence

12.1.1. Human Security in the IPCC Assessment Reports

This chapter assesses the risks climate change poses to individuals and communities, including threats to livelihoods, culture, and political stability. These issues were raised by Working Group II (WGIIAR4) in the Fourth Assessment Report (AR4). That report identified the risk climate change poses to livelihoods (chapters 5, 7, 9 10, 16, and 17), cultures and indigenous peoples globally, but this Chapter is the first systematic assessment across the dimensions of human security.

Both WGIIAR4 and the Special Report on Extremes (SREX) noted the risks climate change poses to: water, soil, food, health and individual well-being. Chapter 7 of WGIIAR4 referred to security as a fundamental social goal, and Chapter 11 noted that the risks climate change poses to national security were poorly understood. It was also noted that migration, crises and violent conflicts increase vulnerability to climate change (Chapter 19). Chapters 7, 16 and 17 of WGIIAR4 noted that migration has the potential to enhance the adaptive capacity.

New research since AR4 has addressed the linkages between climate change and human security (Matthew et al., 2010; O'Brien et al., 2010; Oswald Spring, 2011; Scheffran et al., 2012a; Gleditsch, 2012). Specific dimensions of human security, such as food security; public health and well-being; livelihoods; and regional perspectives are examined systematically in Chapters 11, 13 and 19, and in chapters 22-29 of this report and this Chapter cross-refers to those assessments.

12.1.2. Definition and Scope of Human Security in this Assessment

There are many definitions of human security, which vary according to discipline, emphasis on risk factors, and values. This Chapter defines human security as a condition that exists when the vital core of human lives is protected, and where people have the freedom and capacity to live with dignity. In this assessment, in the context of climate change, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests. Many processes influence human security, notably: the operation of markets, the state, and civil society. Poverty, discrimination of many kinds, and extreme natural and technological disasters undermine human security.

The concept of human security has been informed by many disciplines and multiple lines of evidence and studies that use diverse methods (Paris 2001, Alkire, 2003; Owen 2004, Gasper 2005, Hoogensen and Stuvøy 2006, Mahoney and Pinedo 2007, Brauch et al., 2009, Inglehart and Norris 2012). The concept was developed in parallel by UN institutions (UNDP 1994; Commission on Human Security, 2003); and by scholars and advocates in every regional of the world (Najam 2003, Kaldor 2007, Poku and Sandkjaer 2009, Rojas 2009, Chourou, 2009, Sabur 2009, Othman 2009, Wun Gaeo 2009, Black and Swatuk 2009). In the past decade the linkages between elements of human security, global environmental change and climate change specifically has been examined through international research programmes (for example Matthew et al., 2010; Afifi and Jaeger, 2010; Foresight, 2011; Scheffran et al. 2012a). The assessment in the Chapter is based on systematic reviews. These were carried out firstly using searches of scientific databases of relevant studies published from 2000 till 2013, with searches targeted at the core dimensions of culture; indigenous peoples; traditional knowledge; migration; conflict; and transboundary rivalry. These searches were supplemented by open searches to capture book and non-journal literature.

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Box 12-1. Relationship between Human Rights and Human Security in the Context of Climate Change

Human security is inclusive of political, sociocultural and economic human rights (CHS 2003), which are both an important element of human security, and instrumental to its achievement. Climate change puts human security and human rights at risk (Slade, 2007; Humphreys, 2010; Caney, 2010). Research on climate change risks to human rights examines legal issues in policy, litigation and compensation (Posner, 2007). Several cases have tested these rights, especially of women, children, indigenous peoples, and other minorities in practice (Oswald Spring, 2008). Others argue that rights may not be useful in climate policy (Depledge and Carlane, 2007; Adelman, 2010).

The victims of human rights violations are also vulnerable to climate change impacts. In places with extreme human rights violations, their protection is an important adaption strategy dealing with specific climate impacts (Barnett, 2009).

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This Chapter assesses research on how climate change may exacerbate these and other threats to human security, and how these factors restrict the ability to adapt to climate change. Research on human security focuses on threats to the vital core of lives, including discrimination, economic crises, epidemics, extreme events, and violence (CHS, 2003; Oswald Spring, 2011, 2012). That body of knowledge has shown that underlying processes such as low health status, illiteracy, poverty, and restricted access to economic and social resources, reduce the freedom and capacity of individuals and groups to adapt to climate change, including (CHS, 2003; Betancourt et al., 2010; Goldsworthy, 2010). The systematic review in this Chapter reflects the dominant findings from the scientific literature that the impacts on livelihoods, cultural impacts, migration or conflict are overwhelmingly negative. But the literature on human security also reflects evidence that some elements of human security are not sensitive to climate change impacts, particularly those dimensions that are mainly driven by economics and other social change.

Research on the specific interaction of human security and climate change focuses on how cultural, demographic, economic, and political forces interact with impacts and risks, affecting individuals and communities (Krause and Jütersonke, 2005; Hoogensen and Stuvøy 2006; O'Brien, 2006; Betancourt et al., 2010). The analysis concerns

drivers of vulnerability across multiple scales and sectors, including, gender relations, culture, political institutions and markets. Each of these areas has its distinct disciplinary focus, methods and levels of evidence as discussed in Box 12-2.

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Box 12-2. The Nature of Evidence about Climate Change and Human Security

Understanding the effects of climate change on human security requires evidence about social and environmental processes across multiple scales and sectors. This process-based evidence is not coherent and contiguous; it comes in different forms, and is collected through a wide array of methods used in different academic disciplines. For example, this Chapter assesses anthropological research where culture influences responses to climate change or may be shaped by climate change; alongside political and economic studies which use data sets to test for correlations between climatic factors and violent conflicts; and historical observations using documentary and archaeological methods. These diverse sources strengthen the robustness of the conclusions for this assessment (Van de Noort, 2011; Nielsen and Reenberg, 2012)

Research on human security and climate change relies on theories, models and evidence on how climate variability, anthropogenic climate change and environmental risks affect human security. There is some evidence on causal links in empirical studies.

This Chapter reviews empirical studies from the social sciences using both quantitative and qualitative data, including case studies. Some studies examine the interactions between environmental changes and social outcomes. Few explicitly address climate change and human security links, but some provide evidence of climate change impacts on human security (Ford et al., 2010). Individual case studies often explain causality in given contexts, but their results may not be generalized. Where evidence from multiple comparative case studies agree, generalization is sometimes possible.

This Chapter also assesses quantitative studies about large social units with correlations among different factors. Correlations alone do not explain causality, although they may test theories of causality. The absence of a correlation does not necessarily disprove a causal theory.

Given the complexity of the links between climate change and human security; uncertainties in the research on the biophysical dimensions of climate change; and the nature of the social science, highly confident statements about the effects of climate change on human security are not meaningful (Scheffran et al., 2012a). Yet there is robust evidence about many of the links between climate change and human security: in this Chapter the standardized IPCC language of uncertainty is applied to those areas where appropriate.

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Human security and insecurity are universal issues. In every country there are individuals and groups who are insecure (Mahoney and Pinedo, 2007; Pietsch and McAllister, 2010). Much research suggests that while the impacts of climate change on human security will be experienced most in developing countries, human security is at risk for vulnerable populations everywhere (Naess et al., 2006; Leichenko and O'Brien, 2008; Berrang-Ford et al., 2011;).

The Chapter also evaluates research on the interaction between the state and human security, suggesting that increased human insecurity may rise with an inability to adapt to climate change, thus creating risks to national security through migration and violent conflicts. The analysis extends to assess how states protect the human security of their citizens. In other words, this chapter examines the security of the state insofar as it affects human security by affecting the ability of states to protect their citizens.

The framing of climate change as a security issue has been controversial. Some authors suggest that discourses on climate change and national security tend to downplay human security dimensions, and skew mitigation and adaptation responses towards state interests rather than the most vulnerable (Barnett 2007 and 2009; Brauch, 2009;

Dalby 2009; Floyd 2008; Trombetta 2009; Verhoeven 2009; Oels, 2013). Nevertheless, some countries associate climate change risks with conventional security risks and many countries are concerned about the risks climate change poses to relations between states (see sections 5 and 6). This Chapter therefore adopts a broad approach to human security, which is widely supported in the literature (Barnett, 2001; Brauch et al., 2008, 2009 and 2011; Matthew et al., 2010; O'Brien et al. 2010).

12.2. Economic and Livelihood Dimensions of Human Security at Risk from Climate Change

12.2.1. Climate Change Impacts on Material Aspects of Livelihood Security

Extensive evidence shows that climate change impacts on human security by altering the ensemble of assets, capabilities, entitlements, and activities required for securing a means of living (Battisti and Naylor, 2009; Hertel et al., 2010; Schlenker and Lobell, 2010; Chapter 13). Livelihoods are associated with people's access to five capital assets: social, natural, financial, human and physical. The systematic review on livelihoods and climate change is elaborated in Chapters 8, 9, 13, 18, and 22. Local and indigenous ecological knowledge (Box 18-4), diversification of activities to reduce risks, access to infrastructure and other resources interact together with changes in climate to impact livelihoods (Section 9.2).

To summarise the evidence in cognate Chapters, there are two ways by which climate change impacts upon the material aspects of livelihood security. First, it affects livelihood vulnerability through increasing exposure to shocks and stressors. Climate-related shocks brought about by storms and floods can directly destroy assets and impact on livelihoods (Deligiannis, 2012). Households that are land-less or reliant on climate sensitive capital are particularly vulnerable to such shocks (Chapter 9; Chapter 8; Chapter 22; Chapter 13, Fig. 13.2). Second, climate change can prompt mitigation and adaptation strategies that can advance or undermine human insecurity (Deligiannis, 2012) (Section 12.2.3). Because the most vulnerable and marginalized have low adaptive capacity, they will suffer the greatest impacts from climate change (e.g. Tanner and Mitchell, 2008). Those at greater risk include individuals and households below the poverty line, whose vulnerability is exacerbated by limited access to resources, entitlements, information, and decision-making processes. Much evidence shows that poorer households in both rural and urban areas have higher vulnerability to weather-related risks, with the mechanisms driving this vulnerability discussed in Table 12-1.

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Box 12-3. Gender Dimensions of Human Insecurity

A growing body of evidence indicates that human insecurity associated with climate variability and change is differentiated by gender as well as other social factors (Antwi-Agyei et al., 2012; Arora-Jonsson, 2011; Buechler, 2009; Terry, 2009; Ahmed and Fajber, 2009). In many regions of the world, women have less access to financial resources, land, education, health and other basic rights, and are excluded from decision making processes, making them less able to cope with and adapt to climate change impacts (Djoudi and Brockhaus, 2011; Demetriades and Esplen, 2008; Paavola, 2008). Evidence shows how poor women in developing countries are struggling to protect their lives, homes, assets and livelihoods from weather related hazards . Socially ascribed gender responsibilities for so-called reproductive work, such as childcare, healthcare and domestic work, including the collection of water and firewood, is directly affected by impacts of climate change on nutrition, disease burden and water availability (Denton, 2002).

_____ END BOX 12-3 HERE _____

Table 12-1 summarizes studies on how climate variability and change affects the material aspect of human security. Evidence is categorized under two main dimensions: 1) deprivation of immediate basic needs; and 2) erosion of livelihood assets and human capabilities (Table 12-1). Evidence on the impacts of climate change on basic needs relates to agriculture and food security, water stress and scarcity as well as destruction of homes and properties (Carter et al., 2007; Leary et al., 2008; Peras et al., 2008; Paavola, 2008; Tang et al., 2009). Growing evidence

indicates that climate variability and change disrupts production and income, reduces spending, or alters other common practices of resource-dependent households (Chapter 13). Adverse impacts of climate change on the health and education of children can eventually lead to the erosion of human capability (Costello et al., 2009; UNDP, 2007). Similarly, evidence based on projections using various socio-economic and climate change scenarios indicates an increase in economic and health risks, including loss of lives in both less developed and developed countries (Hall et al., 2003; Tang et al, 2009; Kainuma et al., 2004).

[INSERT TABLE 12-1 HERE
Table 12-1: Observed and projected impacts of climate variability and change on basic needs and livelihoods, and their role in undermining human security.]

12.2.2. Impacts of Adaptation Actions on Livelihood Dimensions of Human Security

Established research methods and evaluations of development interventions provide robust evidence on how livelihoods can be secured in the context of external shocks and how opportunities can be enhanced through adaptation. Much of this research comes from development economics and related disciplines (Elllis, 2000; Dercon, 2004), and is increasingly applied to climate change adaptation studies. Livelihoods can provide people with opportunity (Chapter 13.2.1) and adaptation options that can be transformed into capabilities and assets (Chapter 13.2.1). Adaptation interventions and strategies that have been documented to reduce risks to human security include: 1) diversification of income-generating activities in agricultural and fishing systems (Paavola, 2008; Galvin, 2009; Tolossa, 2008; Badjeck et al., 2010; Coulthard, 2008; West and Hovelsrud, 2010); 2) migration for risk-spreading among pastoralists (Galvin, 2009) and fishers (Badjeck et al., 2009; Perry and Sumaila, 2007); 3) the development of insurance systems (Badjeck et al., 2010); and 4) education of women (Boyle et al., 2006, Rammohan and Johar, 2009).

There is emerging evidence, however, that some adaptation interventions in specific circumstances can decrease human security. For instance, agricultural intensification can initially minimize decline in yield, but may extend household production to marginal and steep lands that can in turn increase soil erosion, nutrient loss or landslides (Deligiannis, 2012).

12.3. Cultural Dimensions of Human Security

12.3.1. How Culture Interacts with Climate Impacts

Culture is analysed in this Chapter as dynamic and encompassing knowledge, worldviews, beliefs, norms, values, social relationships, perceptions of risk, power relations and responses to the world (Crate, 2008; 2011; Heyd, 2008; Roncoli *et al.*, 2009; Strauss, 2009; O'Brien and Wolf, 2010; Tingley *et al.*, 2010; Rudiak-Gould, 2012; Sudmeier-Rieux, 2012). In this definition culture shapes resilience, and drives both adaptive and maladaptive responses (Siurua and Swift, 2002; Pearce *et al.*, 2009; Nielsen and Reenberg, 2010; Petheram *et al.*, 2010; Buikstra *et al.*, 2010; Paul and Routray, 2011). This assessment focuses on the dimensions of culture that maintain identity and a sense of belonging, and that carry potential for creating unequal power relations and conflict.

Climate change is driven by, embedded in, and acts upon culture in myriad ways: consumption and energy use that drives anthropogenic emissions of greenhouse gases, are culturally embedded. And the phenomenon of climate change is perceived through scientific as well as other cultural expressions (Norgaard, 2011). Similarly, there are widely different cultural expressions of weather, risk and the need for adaptation to such hazards (Hulme, 2008; Adger et al., 2013). Since climate change has consequences for people there is high confidence that it also has significant cultural implications (Crate, 2011; Strauss 2012), with knock-on effects for human security.

For many indigenous and rural communities in particular, culture is constructed around livelihood activities such as pastoralism, herding, farming, fishing, and hunting and gathering. Research has documented how livelihoods and cultural practices have been affected by observed changes in diverse direct and indirect climate impacts: seasonal

weather patterns, extreme events, extreme drought and flood cycles, sea level rise, erosion, subsidence, coral bleaching, salinization, species abundance and composition, relocation and increasingly dangerous travel conditions (Oswald Spring et al., 2013). Many of these anthropological studies suggest that further significant changes in the natural resource base upon which many cultures depend, would directly affect the cultural core, worldviews, cosmologies and mythological symbols of indigenous cultures (Crate, 2008; Gregory and Trousdale, 2009; Jacka, 2009). Conversely many cultures have adapted to significant societal and environmental changes throughout history and colonial encounters (Nuttall, 2009; Cameron, 2012; Strauss, 2012). Much research in this area concludes that analysis of cultural understanding of environment, risk and social practices increases the explanatory power of models of risk (Ifejika Speranza *et al.*, 2008; Jacka, 2009; Adger al., 2011).

A further set of research examines cultural, local and individual perceptions and narratives of risk, resilience and adaptive capacity. It finds mixed results: that culturally embedded perceptions in some cases increase human security and in some cases are negative to human security outcomes by way of facilitating or hindering adaptation (Rudiak-Gould, 2012; Gómez-Baggethun *et al*., 2012; Burningham *et al.*, 2008; West and Hovelsrud, 2010; Zamani *et al.*, 2006; Nursey-Bray *et al*., 2012). In scientific studies of how resource-dependent communities articulate climate change, anthropological studies have shown that perception of climate change is often based on how English language terms are translated and understood in the local language (Rudiak-Gould, 2012), and the perception is interpreted through personal lifestories and culture (Kuruppu and Liverman, 2011). Anthropological studies have analysed how the concept of climate change is translated in various cultures and have observed both denial, particularly in situations where religions or cognitive frames do not perceive changing climate (Rudiak-Gould, 2012; Kuruppu and Liverman, 2011; Sánchez-Cortés and Chavero, 2011; Lipset, 2011). This denial of climate change is observed across all societies, and explained by sociological analysis as resulting from paralysis in the face of externally-imposed change (O'Brien and Wolf, 2010; Norgaard, 2011).

Scientific information on weather variability and change is framed through cultural practices: climate forecast or downscaling results are presented but not necessarily understood and assimilated well by, for example, local farmers (Roncoli, 2006). Local perceptions of what kind of knowledge is trustworthy may in fact question both scientific findings (Burns *et al.*, 2010; Ingram *et al.*, 2002) and how to deal with uncertain climate information (Roncoli *et al.*, 2011). Human security is further weakened if (climate) policy does not consider the cosmologies and epistemologies embedded in culture (Jacka, 2009; Stadel, 2008). Table 12-2 illustrates the different dimensions in which climate change is interpreted and against which human security is affected.

[INSERT TABLE 12-2 HERE
Table 12-2: Cultural dimensions of human security in the context of climate change.]

12.3.2. Community and Culture at Risk

Cultural dimensions of climate change are manifest in collective action and community. Community is a contested term in various disciplines (Gibson and Cameron, 2011). Community, as used here, refers to place-based groups that exhibit some form of unity and obligation among the members.

There is a significant body of research that analyses community and collective action for adaptation. Its principal finding is that community-led action is effective for reducing risks and building capacity for adaptation (Davidson *et al.*, 2003; Catto and Parewick, 2008; Harries and Penning-Rowsell, 2011; Gero *et al.*, 2011; Fazey *et al.*, 2010; Furgal and Seguin, 2006; Sudmeier-Riuex *et al.*, 2012; Anik and Khan, 2011; Adler, *et al*., 2012). Specifically this literature finds that community participation in risk and vulnerability assessments produces more sustainable solutions (Ardalan *et al.*, 2010; Gero *et al.*, 2011) and that so-called co-management and learning, increases adaptive capacity (Fazey *et al.*, 2010; Armitage *et al.*, 2011; Dumaru, 2010; Ford *et al*., 2007). Caveats to such analysis highlight structural barriers to community-led action and shows that participation in collective action is limited by hierarchical power relations (Singleton, 2000; Herbert, 2005; Davidson *et al.*, 2003; King, 2008; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Onta and Resurrection, 2011).

Table 12-2 reports on evidence across issues of culturally-determined perceptions of climate risks and responses. It highlights major findings that flexibility and livelihood diversification are two key factors in successful adaptation to variability in resource abundance (de Sherbinin *et al.*, 2008; Desta and Coppock, 2004; Ford *et al.*, 2006; Kalikoski *et al.*, 2010; Hovelsrud *et al.*, 2010a,b; Rybråten and Hovelsrud, 2010; McNeeley, 2011; Marshall 2011; Eakin *et al*., 2012; Ford and Goldhar, 2012; Berkes and Armitage, 2010). Further evidence suggests that changing socio-economic and environmental conditions may constrain existing coping community mechanisms (Rattenbury *et al.*, 2009; West and Hovelsrud, 2010; Quinn *et al.*, 2011). Local community responses are also shaped by political and economic globalization, in terms of a decoupling of production- and political networks from the local level (Keskitalo, 2009), and by colonial history (Marino, 2012).

12.3.3. Indigenous Peoples

There are about up to 500 million indigenous people worldwide (see Glossary for an inclusive definition), living under a wide range of social, economic and political conditions and locations (Nakashima *et* al., 2012). Indigenous peoples represent the world's largest reserve of cultural diversity and the majority of languages, and assessments of the cultural implications of climate change for human security illustrate similarities across geographical regions and climatic conditions. For many indigenous communities, there are significant linkages between historical colonization and current climatic changes (Cameron 2012; Howitt et al 2012; Salick and Ross 2009; Marino, 2012). It is argued in some literature that research on climate change in regions with significant indigenous populations often has assumptions concerning indigenous peoples being more connected to place than others (Cameron 2012) while scientists and indigenous peoples are increasingly using hybrid knowledge across scientific and traditional domains (Huntington 2011).

To a great extent the livelihood and culture of indigenous peoples are closely connected to natural resources, and in many parts of the world they are economically and socially marginalized (Crate and Nuttall, 2009). There is a *general agreement* that historically indigenous peoples have a high adaptive capacity to highly variable environmental conditions, but less so with respect to rapidly changing socio-economic conditions and globalization (Tyler *et al.*, 2007; Crate and Nuttall 2009). Conversely, the lack of adaptation to colonization and globalization may reflect resilience and the determination of indigenous peoples to maintain cultures and identities - and so does not necessarily indicate low adaptive capacity. The challenge of maintaining cultures and livelihoods will be exacerbated by climate change (Crate and Nuttall 2009; Rybråten and Hovelsrud, 2010). Such risks are exacerbated when: traditional practices – including those related to mobility - no longer prove effective in responding to climate variability (Green *et al.*, 2010); governments relocate communities (Hitchcock, 2009; McNeeley, 2011); policy and disaster relief creates dependencies (Wenzel, 2009; Fernandez-Gimenez et al. *et al.*, 2012); there are inadequate entitlements to resources (Shah and Sajitha, 2009); income inequality within and between communities increases (Green *et al.*, 2010); there are constraints to the transmission of language and knowledge between generations (Forbes, 2007).

Climate change poses challenges for indigenous peoples, including to their knowledge systems, cultural practices, adaptive strategies, and post-colonial power relations. The extensive literature on the Arctic shows that for indigenous peoples the changing ice conditions pose risks in terms of access to food, and dangerous travel conditions (Ford *et al.*, 2008; Ford *et al.*, 2009; Hovelsrud *et al*., 2011a). Additionally there are uneven societal consequences related to sea ice use, local physiological setting and community socio-cultural dynamics (Ford *et al.*, 2008), illustrating the heterogeneity within indigenous groups found elsewhere (Barrett, 2001).

Some studies show that current indigenous adaptation strategies may not be sufficient to meet the projected changes (Wittrock *et al.*, 2011. Indigenous peoples are often portrayed as victims of climate change (Salick and Ross 2009), and as vulnerable to the consequences (ACIA 2005), with implications for their human security. Indigenous peoples have a right to maintain their livelihoods and their connections to homeland and place (Howitt *et al.*, 2011), and it is suggested that the consequences of climate change are challenging this right (Box 12-1; Crate and Nuttall 2009). Some raise the question whether the western judicial system can uphold indigenous rights in the face of climate change (Williams 2012).

Much research with indigenous peoples concludes that lack of involvement in resource management decreases resilience and thereby human security, and that it is necessary to focus on indigenous perceptions of risk and traditional knowledge of change, hazards and coping strategies and collective responses (Ellemor, 2005; Finucane, 2009; Turner and Clifton 2009; Sánchez-Cortés and Chavero, 2011; Brown, 2009). Tourism development and industrial activities are particular risks for indigenous peoples when they are not involved in decision-making (Petheram *et al.*, 2010). Lack of formal participation in international policy and management negotiations may pose risks for indigenous peoples because their perspectives may not be heard (Schroeder, 2010), and there are examples of successful indigenous lobbying and advocacy in the case managing persistent organic pollutants and heavy metals in the Arctic (Selin and Selin, 2008).

12.3.4. Local and Traditional Forms of Knowledge

There is *agreement* among researchers that involvement of local people and their local, traditional or indigenous forms of knowledge is critical for ensuring human security (Ellemor, 2005; Kesavan and Swaminathan, 2006; Burningham *et al.*, 2008; Mercer *et al.*, 2009; Pearce *et al.*, 2009; Anik and Khan, 2012). We define such forms of knowledge (also traditional ecological knowledge, farmers' knowledge, indigenous science, ethnoscience) (Nakashima and Roué, 2002) as 'a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations' (Berkes 2012: 7). In addition to reasserting culture, identity and traditional values, such forms of knowledge are experiential, dynamic, and highly context dependent, developed through interactions with other forms of knowledges, including scientific, and viewpoints (Ford *et al.*, 2006; Orlove *et al.*, 2010; Sánchez-Cortés and Chavero, 2011; Eira *et al.*, 2013).

Although some studies warn that the emphasis on the value of local/traditional knowledge may be overrated, such knowledge is increasingly seen as a critical source for understanding change, for identifying socio-economic aspects, for developing adaptation strategies and policies, as critical input to climate scientists. For example, such knowledge serve as a basis for forecasting local weather, and provide the necessary insights about the local climate elements needed for relevant meteorological forecasting (Nyong *et al.*, 2007; Tyler *et al.*, 2007; Gearheard *et al.*, 2010; Hovelsrud and Smit, 2010; Orlove *et al.*, 2000). Local and traditional knowledge are often not included in adaptation planning (King *et al.*, 2007; Ifejika Speranza *et al.*, 2008; Tàbara *et al.*, 2003), or not valued or pursued properly in scientific studies (Huntington: 2011).

Local andtraditional knowledge about historical changes and events, and adaptation strategies to changing conditions are valuable for evaluating responses to change and policy (Angassa and Oba, 2008; Desta and Coppock, 2004; Eira *et al.*, 2013; Ford *et al.*, 2008; Lefale, 2010; Osbahr *et al.*, 2010; Orlove *et* al., 2000; Fernández-Giménez, *et al.*, 2012). It is an important contribution for mitigating natural disasters (Rautela, 2005), maintaining domestic biodiversity (Emperaire and Peroni, 2007), and developing sustainable adaptation and mitigation strategies (Nyong *et al.*, 2007). Among the Borana in Africa indigenous pastoralists' technical and organizational practices have been ignored in development, which has contributed to progressive land degradation, erosion of social structures, and poverty (Homann *et al.*, 2008). Evidence from mountain regions exposed to floods illustrates that incorporation of local knowledge into policy and decision-making reduces risk (Alcántara-Ayala et al., 2004).

Local and traditional knowledge are living resources (Nakashima and Roué 2002; Berkes 2012;) and can be retained through intergenerational transmission, its integration with other forms of knowledge (King and Goff, 2010; Kalanda-Joshua *et al.*, 2011), and its utilization in monitoring and assessments (Klintenberg *et al.*, 2007; Kalabokidis *et al.*, 2008) and in disaster risk management (Becker *et al.*, 2008; Mercer *et al.*, 2009; Pareek and Trivedi, 2011; Bilbao *et al.*, 2010; Kalabokidis *et al.*, 2008). There is *strong evidence* that mutual integration and co-production of local and traditional and scientific knowledge will enhance resilience, increase adaptive capacity and reduce vulnerability (Kofinas, 2002; Oberthür *et al.*, 2004; Tyler *et al.*, 2007; Anderson *et al.*, 2007; Vogel *et al.*, 2007; West *et al.*, 2008; Armitage *et al.*, 2010; Frazier *et al.*, 2010; Marfai *et al.*, 2008; Flint *et al.*, 2011; Ravera *et al.*, 2011; Nakashima *et al.*, 2012; Eira *et al.*, 2013).

Although local stakeholders and scientists may identify competing opportunities and constraints when attempting to reconcile for example local development with resilience to natural hazards (Frazier *et al.*, 2010), the interface

between scientific and local, traditional or indigenous knowledge can be seen as a source of inventiveness rather than where validity of knowledge is contested (King and Goff, 2010). Conversely, projects integrating climate projections and local observations reveal different results or discontinuities, often attributed to different perspectives and cultures (Marin, 2010; Mark *et al.*, 2010). This creates barriers for integration (Kwiatkowski, 2011; Ravera *et al.*, 2011), illustrating the need for incorporating local and indigenous knowledge and observations into climatology, and for creating locally relevant and trustworthy climate projections (Ingram *et al.*, 2002; Ifejika Speranza *et al.*, 2008; Smit et al 2010).

There are many challenges in managing, utilizing, acknowledging and incorporating these forms of knowledge (Huntington 2011), and the participatory approach may not be sufficient because of the cultural and social dynamics of power and interpretation (Roncoli *et al.*, 2011). Some studies suggest that local/traditional knowledge may not be sufficient to provide the proper response to surprising or infrequent risks, hazards or events (Nunn, 2000; Burningham *et al.*, 2008; Kuhlicke, 2010). Additionally if local/traditional knowledge is perceived to be less reliable because of changing environmental conditions (Ingram *et al.*, 2002; Ford *et al.*, 2006), or because of extreme or new events that are beyond the current local knowledge and cultural repertoire (Valdivia *et al.*, 2010; Hovelsrud *et al.*, 2010a), then community vulnerability, and the vulnerability of local/traditional knowledge itself, may increase (Kalanda-Joshua *et al.*, 2011). In the case of coastal communities in India, the societal and environmental conditions have changed to the point at which local knowledge is no longer as applicable as it was in the past (Kesavan and Swaminathan, 2006). In the Himalayas erosion of local/traditional knowledge occurs through government regulations of traditional building materials and practices. The social cohesion embedded in such practices is weakened because of a move towards concrete construction which changes the reliance on and usefulness of traditional knowledge about wood as building material (Rautela, 2005). New conditions may require new knowledge to facilitate and maintain flexibility and improving livelihoods (see also Homann *et al.*, 2008).

12.4. Migration and Mobility Dimensions of Human Security

12.4.1. Impacts of Climate Change on Displacement, Migration, and Mobility

12.4.1.1. Nature of Evidence on Climate Change and Migration

Migration is prevalent in every part of the world, driven by economic and other imperatives. Existing migration systems may be significantly disrupted by impacts of climate change in a number of important dimensions. Migration, defined in terms of temporal and spatial characteristics, is generally classed as a permanent or semi-permanent move by a person of at least one year that involves crossing an administrative but not necessarily a national border. As a result, migrants alter their baseline population of reference and their local networks (Brown and Bean, 2005).

The most significant contemporary trend in migration by volume of movement continues to be major movements of people from rural to urban settlements. The proportion of the global population that is urban has risen from 10 percent in 1900 to over 50 percent in 2009 and is projected to reach 59 percent by 2030 (UNDP 2009; Grimm et al., 2008). Around 80 percent of all migration is presently within countries. Existing global migration trends mapped onto ecological zones by de Sherbinin et al. (2012) show that the past four decades have seen out-migration from mountain regions and from drylands. Net migration to coastal zones was over 70 million people in the 1990-2000 census period, even though cities and coastal zones themselves are at risk from the impacts of climate change.

As with other elements of human security, the dynamics of interaction with climate change are multi-faceted and direct causation is difficult to establish. There is a growing literature on the demographic, economic and social processes of climate migration interactions (Afifi and Jäger 2010; Piguet et al., 2011; Serrano Oswald et al., 2013). The major emphases are on disentangling causation and multiple drivers of migration; displacement of populations from extreme events; governance challenges and the rights of international migrants and displaced peoples; and on the challenges of migration for urban sustainability and climate impacts (Foresight 2011; Black et al., 2011a,c; White, 2011a; Parnell and Walawege, 2011; Seto, 2011 Geddes et al., 2012;).

The most common methods used to examine the actual processes of migration and climate change risks include statistical inference to explain observed migration patterns with climate or related impacts as independent variables; sample surveys of actual migrants to explain their individual drivers of the decision to migrate; and other modeling techniques and indepth qualitative studies designed to explain the social processes and context by which migration decisions are made, often using historical analogies (McLeman and Hunter, 2010; Piguet, 2010). Some modeling studies project impacts of climate change on the viability of continued habitation and examine the impact of rainfall decline or land inundation as a risk factor for the displacement of people. These studies have, for risks such as sea level rise, quantified potential displacement (Nicholls et al., 2011). As with all the major elements of human security in this Chapter, the issue of causality between environment or risk and the human security outcomes of migration are not established.

12.4.1.2. Do Climate Change Impacts Increase Displacement or Restrict Mobility?

It is widely established that extreme weather events displace populations because of their loss of place of residence or economic disruption. This Section reviews evidence on how displacement is highly differentiated socially and has significant economic and social costs (Hallegatte, 2012). Much of the literature, such as reviewed in IPCC SREX report, concludes that with an increasing incidence and changing intensity of extreme weather events due to climate change, there may be increased levels of displacement.

Much evidence shows a distinct temporal dimension to displacement ranging from localised and short-term movement of people, through intra-regional migration to international displacement as a result of large-scale events. The Pakistan floods of 2010 caused primarily localised displacement for large numbers of people across a wide area (Gaurav et al., 2011). The evidence on displacement as a result of climate-related extremes suggests that most displaced people attempt to return to their original residence and rebuild as soon as practical.

In general, structural causes of vulnerability, such as income inequality, race, class, and discrimination, deeply affect the livelihood drivers of displacement and the consequences of return. The migration associated with Hurricane Katrina, for example, shows that in New Orleans economically disadvantaged populations were displaced in the immediate aftermath and have not returned (Myers et al., 2008). Fussell et al. (2010) found that 14 months later black residents returned more slowly, because they had suffered greater housing damage. Adams et al. (2009) identified factors that have led to a ‘chronic disaster syndrome’ where some populations are unlikely to return, and Hori and Shaefer (2010) suggest that displacement affected human security through housing, economic and health outcomes. There is also evidence of gender differentials in displacement from extreme events, especially when they lose their social networks or their social capital, and are often affected by adverse mental health outcomes in situations of displacement (Tunstall et al., 2006; Oswald Spring, 2008; Hunter and David, 2011).

Structural vulnerabilities affect the ability to cope with climate change and extreme events without migrating. Hurricane Mitch in 1990 affected different Central American countries and displaced up to two million people either temporarily or permanently. The impact was highly differentiated by country, with much lower displacement rates in Belize compared to Nicaragua, Honduras and El Salvador, with large scale displacement and an increase in international migration of 300 percent from Honduras (Glantz and Jamieson, 2000; McLeman and Hunter, 2010). But the impacts of such events are highly uneven. While the poorest households in Honduras were hardest hit by the hurricane (McSweeney and Coomes, 2011), they were less vulnerable to storms a decade later due to changes in land tenure and better early warning systems (Villagrán, 2009).

Not all populations are displaced by extreme weather events. A further strand of evidence on migration shows social differentiation in access to the resources necessary to migrate (Renaud et al., 2011; Black et al., 2012). A review by Black et al. (2012) proposed that populations that are trapped through lack of mobility. Figure 12-1 illustrates these dynamics, showing how vulnerability is inversely correlated with mobility, leading to those being most exposed and vulnerable to the impacts of climate change having the least capability to migrate. Therefore, climate change risks may be most significant when they reduce and constrain opportunities.

[INSERT FIGURE 12-1 HERE
Figure 12-1: Relationship between vulnerability to environmental change and mobility. Lack of mobility and high vulnerability are positively correlated. Adapted from Black et al. (2013).]

One consistent theme of the hazards literature is that while migration responses are common, movement is costly and disruptive and hence may only be used as an 'adaptation of last resort' (McLeman, 2009). Paul (2005) found that there was little displacement in Bangladesh as a result of flooding in affected villages and that residents perceived an influx of migrants due to the reconstruction. Hurlimann and Dolnicar (2011) showed for eight Australian settlements that relocation and migration was perceived to be the least desirable adaptation. Haug (2002) showed that pastoralists displaced due to drought in Sudan in the 1990s attempted to return to their previous settlements after the drought, notwithstanding conflict and other factors. McLeman and Hunter (2010) reviewed historical cases of displacement migration and concluded that non-migration or rapid return migration significantly outweighs permanent migration following hurricane impacts in the Caribbean, Dust Bowl migration in the 1930s USA, or dry season migration in the West African Sahel.

Table 12-3 summarises studies on weather extremes and long-term environmental change with migration outcomes showing that some events and trends lead to increased displacement of populations (column 1); while others lead to reduce mobility and significant trapped populations (column 2). Table 12-3 also demonstrates that in many circumstances (column 3) sections of populations are differentially affected, on the basis of ethnicity, wealth or gender (Elliot and Pais, 2006; Gray and Muller, 2012; Upton, 2012). Table 12-3 therefore demonstrates that the key impacts of climate change include increased displacement; reduced mobility and trapped populations; and migrant populations moving towards destinations likely to be more hazardous due to the impacts of climate change (Black et al., 2011a).

[INSERT TABLE 12-3 HERE
Table 12-3: Empirical evidence on observed or projected mobility outcomes (migration, immobility, or displacement) associated with weather-related extremes or impacts of longer-term climate change.]

Studies highlight that long distance migration is reduced by drought in pastoral systems and hence is experienced as reduced mobility (Findley, 1994; van der Geest, 2011; Sánchez et al., 2012). All pioneer migration to urban centres requires significant human and financial capital and hence is restricted to wealthier populations. Henry et al. (2004) confirmed in a multi-year study of Burkina Faso that the movement to other rural areas increased in dry years, but long distance or international migration was limited to years of high agricultural productivity. Kniveton et al. (2011) model migration movements from the 1980s in Burkina Faso and project that future scenarios of decreased rainfall would significantly increase rates of out-migration from rural areas.

Displacement migration as an adaptation to environmental change has a potential interaction with conflict: increased demands on local resources and services can create competition with resident populations, or where there is ethnic tension and distrust between migrants and residents (Reuveny, 2007; Warner et al., 2010; Hendrix and Salehyan, 2012). Evidence in this area is mixed. There is no established consensus on relationships between resource scarcity (whether the initial state or resulting from immigration) and conflict (Section 12.5; Hendrix and Salehyan, 2012). An analysis of multiple cases of large scale population displacement in Africa (from causes such as civil war and conflict) report that significant conflict emerged in receiving areas in around 50 percent of cases, and is less likely when migrants and residents are of the same ethnicity and religion (Reuveny, 2007). Conversely, conflict, particularly large-scale violent conflict, can lead to displacement. This is most common where much of the population is dependent on the environment for livelihoods, as conflict impacts the ability of communities to access resources and respond to environmental variation, increasing the propensity for migration out of the area (Raleigh, 2011). That such displacement may initiate new conflict in receiving areas indicates the complex nature of conflict, and that migration will simply be one contributing factor.

There is some evidence that new migrants are more at risk in cities for two reasons. First, low income migrants are vulnerable to labour market discrimination, access to services such as health care and to crime and violence (McMichael et al., 2012; Fox and Beall, 2012). Second, low-income migrants cluster in high-density areas with exposure to flooding and landslides, with these risks increasing with climate change (Chatterjee, 2010; McMichael

et al., 2012). Migrants in Buenos Aires, Lagos, Mumbai and Dakar (Chatterjee, 2010; World Bank, 2010; Mehrotra et al., 2011) are more likely to be exposed to weather-related hazards than long-term residents. In Dakar (1998-2008), 40 percent of new migrants resided in areas with high flood risk. Wang et al. (2012) found that migrants had less knowledge about typhoon risks in Shanghai. Tompkins et al. (2009) showed that new migrants in the Cayman Islands are most vulnerable to tropical cyclones as they are least likely to prepare for cyclones, live in locations with high exposure to cyclone impacts, and interact mostly with expatriates without previous cyclone experience. There is no established evidence that rapid urbanization itself is a source of conflict: Buhaug and Urdal (2013) test hypotheses on social disorder and population growth in 55 cities in Africa and find that rapid growth of city populations does not drive urban unrest.

12.4.1.3. Migration Trends and Long-Term Climate Change

Long-term environmental change, sea-level rise, coastal erosion, and loss of agricultural productivity (Table 12-3) will have a significant impact on displacement. Barbieri et al. (2010) estimated emigration rates in Brazil from affected rural areas and found that de-population occurs with relatively modest rates of warming. In their scenarios the biggest increase in migration comes from productive agricultural areas that support a large labour force. Medelsohn et al. (2007) concluded that in dryland Brazil urban migration is highly likely due to agricultural income loss.

Longer term environmental change caused by climate change also amplifies existing trends such as rural to urban migration, though results diverge on the importance of climate change and resource scarcity. Modelling studies with future projections on Mexico-US migration rates (Feng et al., 2009), and on Brazilian internal migration (Barbieri et al., 2011) show that projections of drying increase emigration in established migration routes and de-population of rural areas (Kniveton et al., 2011). Barrios et al. (2006) used statistical modelling of changes in rainfall to explain migration rates to African cities. They observed rainfall decreases during the past fifty years and showed statistically they only partially explained differences in urbanization rates, with shortages in rainfall increasing urbanization in sub-Saharan Africa, but often propelled by simultaneous liberalization and policy change.

Nicholls et al. (2011) estimate displacements based on potential sea-level changes till 2100. A 0.5m sea-level change implies a likely land loss of 0.877 million km^2 by 2100, displacing 72 million people, with no adaptation investment and with 2.0 metres, 1.789 million km^2 would be lost, displacing 187 million people, or 2.4 percent of global population, mostly in Asia. If all coasts were protected with dikes and beach nourishment, these estimates fall to 0.041-0.305 million people displaced by 0.5-2.0 m of sea level rise. Hallegatte et al. (2011) assume that such protection measures are very likely as the cost of not investing in protecting urban land and infrastructure is so great. Existing migration trends are also likely to exacerbate impacts of climate change and vulnerability themselves. There is a well-documented drift of population into coastal and regional settlements. Curtis and Schneider (2011) project 12 million people to be affected by sea-level rise by 2030 in four major coastal areas in the US.

Even in areas under threat from long-term climate change, individual migration decisions and aggregate flows are embedded in economic and cultural imperatives. Mortreux and Barnett (2009) found that migration from Tuvalu was not driven by perceptions of climate change and that despite forecasts that the island could become uninhabitable, residents have remained for reasons of culture and identity. Shen and Gemenne (2011) concur that both Tuvalu residents and migrants from Tuvalu in New Zealand did not cite climate change as a reason for movement. Both studies also argue that environmental risks directly affect perceptions of potential well-being and economic opportunities: hence the impacts of climate change may be a more significant driver of future international migration. Observational studies of international migration show that past migration flows are the greatest predictors of future flows because of identity and cultural linkages in both source and destination regions (Serrano Oswald, 2013).

12.4.2. Migration as an Adaptation to Climate Change Impacts

From a human security perspective, migration is a widely used adaptation strategy that reduces risks in highly vulnerable places. Studies have outlined the social processes by which migration reduces vulnerability, and often conclude that a greater emphasis on mobility within adaptation policies would be effective (Barnett and Webber, 2010; Bardsley and Hugo, 2010; Warner, 2010; Gemenne, 2011). This emerging literature focuses on four areas of government intervention: a) social protection mechanisms such as cash transfers to reduce the likelihood of temporary displacement from weather-related extremes (Johnson and Krishnamurthy, 2010); b) adaptation in destination regions, by reducing the vulnerability of migrants in growing urban areas; c) protection and assistance of migrants as they move with rights to citizenship and ability to make economic linkages back to source regions and countries (Fox and Beall, 2012; Martin, 2012); and d) dealing with the prospect of relocation of settlements.

With observed climate changes, such as melting permafrost, and projected changes in resource productivity and risks, various governments are engaged in planning to move settlements as part of adaptation strategies (de Sherbinin et al., 2011). Scientific literature on these policies most often portrays resettlement as a failure of adaptation and a policy of last resort (Barnett and Webber, 2010; Fernando et al., 2010; Hugo, 2011; de Sherbinin et al., 2011). Most of the evidence to date, learning from other resettlement programmes, demonstrates negative social outcomes for those resettled, often analysed as breaches in individual human rights (Johnson, 2012; Bronen, 2011). There is some documented examples of settlements that are already planning for their own relocation, such as five indigenous communities in Alaska that are threatened with increased erosion, loss of ice cover and flooding over the past decades (Bronen, 2010). These settlements have undertaken planning for relocation and have received government funding for these processes. In line with all major analyses in this area, Bronen (2010) concludes that while the relocations are feasible, cultural and psychological elements at individual and community level are difficult to assess. There is significant resistance to relocation, even where such options are well planned and have robust justifications, as demonstrated by (Marino, 2012) for relocation in Alaska.

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Box 12-4. Evidence on the Existence of Environmental Migrants and International Policy to Protect Them

Legal and political research has shown that the term climate refugee is not meaningful. First, the quantified global estimates of 'environmental refugees' proposed by Myers (2002) and others, for example, and repeated in policy documents, have been widely criticised (Black et al., 2011a; Taccoli, 2009; Piguet, 2010; Gemenne, 2011; Jakobeit and Methmann 2012; Bettini, 2013). Most present research focuses on the multiple drivers and on migration processes and shows that models of displacement fail to include other adaptation strategies and that quantifying displacement as the prime migration issue fails to account for the reality of migration systems and existing flows.

Second, there is widespread agreement in the scientific and legal literature that the use of refugee in this context is 'erroneous as a matter of law, and conceptually inaccurate' (McAdam, 2011, p. 102). The arguments put forward for a specific legal instrument to deal with migrants who have been displaced as a direct result of climate change impacts include issues of rights given that such migration is imposed and involuntary (Bell, 2004); the scale of the potential issue with the potential for large populous areas to be inundated in the future due to sea level rise in particular (Bates, 2002); and the particular status of small island nations where displacement could affect sovereignty (Biermann and Boas, 2009; Williams, 2008; Owens, 2008).

For international displacement and migration, there is a growing literature on the nature of displacement; whether there are governance mechanisms facilitating migration at present; and the optimal design of such mechanisms in future (e.g. Biermann and Boas 2009, Williams, 2008; Bryavan and Rajan, 2006; Docherty and Giannini, 2009; Martin, 2009; McAdam, 2011). This literature focuses on strategies for adaptation, mitigation and resilience building, and concludes that significant adaptation may be required to protect and to empower internal or international migrants triggered by climate change. Several legal proposals have been analysed by socio-legal studies suggesting new multilateral conventions, or compensation mechanisms to countries where the population is forced to migrate (Bierman and Boas, 2012).

New international governance mechanisms for international displacement address the difficulties to develop such an instrument in international law. Most migration and climate studies point to the environment as triggers and not causes for migration decisions. Some studies focus on the geo-political implications of changing the Geneva Convention on refugees to include environmental migrants as well as the lack of global instruments to handle internal displaced peoples or international migrants (Martin, 2009; Cournil, 2011). Others discuss the implications of climate migrant status in international migration, where full citizenship and economic status in destination countries are often not realised (McAdam, 2011; Hartmann, 2010). Many small island countries are reluctant themselves to have their international migrants designated as being victims of climate change (McNamara and Gibson, 2009; Farbotko, 2010; Fabrtoko and Lazrus, 2012; Barnett and O'Neill, 2011).

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12.5. Dimensions of Conflict and Vulnerability to Climate Change

12.5.1. Climate Change as a Cause of Violent Conflict

In the past decade there has been a significant increase in research investigating the interactions between climate change and violent conflict, reflecting policy discourses that climate change impacts and resource scarcity could escalate conflict risks. Changes in climate will bring groups of people into conflict over property rights, markets, and public goods. Offsetting those risks, there is evidence that in specific circumstances resource scarcity drives adaptation and innovation (Butzer 2012, Gausset and Whyte 2005, Mehta 2010). And resource scarcity rarely escalate to violence, and violent conflict itself has generally become less common and less intense since 1991 (Goldstein 2011, Themnér and Wallensteen 2012). Risks between climate change and conflict are defined as emerging in Chapter 19 (19.4) as this is a new area of research. This Chapter concludes that there are multiple interactions between conflict and climate change impacts, and that some well established contributing factors to conflict are sensitive to climate variability and change.

There is a modest amount of research that explores the relationship between large-scale disruptions in climate and the collapse of past empires (using statistical analysis and data derived from archaeological and other historical records). For example, the timing of the collapse of the Khmer empire in the Mekong basin in the early 15th century corresponds to an unusually severe prolonged drought (Buckley et al 2010). DeMenocal (2001) summarizes evidence that suggests that major changes in weather patterns coincided with the collapse of several previously powerful civilizations, including the Anasazi, the Akkadian, Classic Maya, Mochica, and Tiwanaku empires. The precise causal pathways that linked these changes in climate to changes in civilizations are not well understood due to data limitations. This evidence from historical antecedents cannot be taken to mean future changes in climate will lead to large-scale political collapse due to diverse changes and globalization in the contemporary world (Butzer 2012).

A modest body of research shows that the Little Ice Age was associated with more cases of political upheaval and warfare than in any other period (Parker 2008, Zhang et al 2011), including in Europe (Tol and Wagner 2010), China (Brook 2010), and the Ottoman empire (White 2011b). These studies all show that climate change can exacerbate major political changes given certain social conditions, including a predominance of subsistence producers, conflict over territory, and autocratic systems of government with limited power in peripheral regions.

There is very little research that explores the risks that climate change poses to violent conflict between states in the past half century. Most recent studies agree that systemic trends towards peace between countries are unlikely to be affected by the impacts of climate change, even with respect to expected changes in transboundary rivers (Bernauer and Siegfried 2012, Brochmann and Hensel 2009, Dinar et al 2011, Feitelson et al 2012, Gartzke 2012, Goulden et al., 2010, Tir and Stinnett 2012, Wolf 2007). All studies show that there are robust institutions that mediate information and create commitments to shared solutions to manage the transboundary impacts of climate variability. The growth and improved capacity of these institutions is major reason why war between states is increasingly rare (Goldstein 2011).

There is a modest amount of research that finds an association between increases in temperature and violent crime (Anderson 1987, Anderson 2001, Breetzke and Cohn 2012, Butke and Sheridan 2010, Field 1992, Gamble and Hess 2012, Rotton and Cohn 2001). Theories that explain that pathways between higher temperatures and violent crime are contested (Breetzke and Cohn 2012, Gamble and Hess), and there is also debate about the effect of very high temperatures on violent crime, with some evidence showing that violent crime falls in conditions of extreme heat (Gamble and Hess 2012, Rotton and Cohn 2001). These debates highlight uncertainties that limit conclusions about the effects of climate change on violent crime. Evidence for this relationship between temperature and violent crime is mostly from cities within the United States, and from crime data in recent decades, whereas historically, and globally, rates of violent crime generally fall as per capita wealth increases (Cole and Gramajo 2009, Neumayer 2003). Studies that seek to discover the major causes of violent crime do not identify temperature and other climate variables are significant, with factors relating to culture, income, and policy explaining most of the variation between countries and over time (Cole and Gramajo 2009, Fajnzylber et al 2002, Karstedt 2001, Kawachi et al 1999, Neumayer 2003).

Most of the research on the connections between climate change and violent conflict focuses on the connections between climate change and civil war. For the most part this research examines rainfall or temperature variability as proxies for the kinds of longer-term chances that might occur due to climate change (see also Chapter 19). One study examines the relationship between temperature and violent conflict (Burke et al. 2009), although this has been challenged (Buhaug 2010). The vast majority of studies seek evidence from Africa, and using satellite-enhanced rainfall data collected since 1980. A global study by Hsiang et al (2011), finds that since 1950 and in countries that are teleconnected to ENSO the risk of war within countries rises during an ENSO period. This study is supported by some studies that find associations between deviations in rainfall and civil war (Miguel et al. 2004, Hendrix and Glaser 2007), but contradicted by others that find no significant association between droughts and floods and civil war (Buhaug 2010, Buhaug and Theisen 2012, Theisen et al., 2012, Slettebak 2012). Examination of individual conflict shows that there is no prospect of identifying specific civil wars as being primarily driven by climate. Box 12-5 demonstrates multiple resource and political dimensions of the Darfur conflict with no studies concluding that the conflict was climate-driven.

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Box 12-5. Climate and the Multiple Causes of Conflict in Darfur

Climate variability is popularly reported to be a significant cause of the mass killing in the Darfur region that began in 2003 (see Mazo 2009): long term drought and vulnerability of the population to drought has been identified as the trigger and cause. Five detailed studies of the conflict conclude that climate variability and related environmental changes are proximate but not primary causes of the violence.

The detailed studies find that the violence in Darfur has multiple causes, notably:

- The legacy of past violence, which established groups that had a history of violent action, and a supply of weapons
- Manipulation of ethnic divisions by elites in Khartoum
- Weakening of traditional conflict resolution mechanisms through government policies, and as a consequence of famines
- Systematic exclusion of local groups from political processes, including of the Fur, Masalit, and Zaghawa ethnic groups
- Limited economic development and inadequate provision of public services and social protection, stemming from governance and policy failures, political instability, and misuse of official development assistance
- Desertification, declining productivity of arable land, and increased aridity.

(Brown 2010; Hagen and Kaiser 2011, Kevane and Gray 2008, Sunga 2011, Verhoeven 2011)

All analyses agree that it is not possible to isolate any of these specific causes as being most influential (Hagen and Kaiser 2011, Kevane and Gray 2008, Sunga 2011, Verhoeven 2011). Most authors identify government practices as being far more influential drivers than climate variability, noting also that similar changes in climate did not

stimulate conflicts of the same magnitude in neighboring regions, and that in the past people in Darfur were able to cope with climate variability in ways that avoided large scale violence.

These studies therefore dispute the identification of the Darfur conflict as being caused by climate change, arguing that attributing this conflict to climate change masks the culpability of actors and the major drivers of insecurity.

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There remains significant disagreement about the nature of the evidence and the strength of the conclusions that can be drawn from it. There is agreement that climate is only one factor in the risk of civil war, and that where other risk factors are extremely low (such as where per capita incomes are high, and states are strong democracies), the impact of changes in climate on civil war is negligible (Bernauer et al 2012, Koubi et al 2012, Scheffran et al. 2012a).

A growing body of research examines the connections between climate variability and smaller scale violent conflicts (communal violence). There is some agreement that both increased rainfall and decreased rainfall in resource-dependent societies enhances the risk of localized violent conflict, particularly in pastoral societies in Africa (Adano et al 2012, Butler and Gates 2012, Hendrix and Salehyan 2012, Raleigh and Kniveton, 2012, Theisen 2012). In all such cases, the presence of institutional structures that protect property rights and manage conflict are highlighted as the critical factors in mediating such risks (Adano et al. 2012, Benjaminsen et al., 2012, Butler and Gates 2012, Hidalgo et al. 2010, O'Loughlin et al 2012, Gausset 2005, Theisen 2012).

In response to the challenges of finding direct associations between changes in climate and violence, some research has examined the effects of changes in climate on factors that are known to increase the risk of civil war (Berholt and Lujala 2012, Koubi et al. 2012). Civil war has been studied extensively using quantitative and qualitative techniques, and there is strong agreement about factors that increase the risk of civil war, namely: a recent history of civil violence, low levels of per capita income, low rates of economic growth, economic shocks, inconsistent political institutions, and the existence of conflict in neighboring countries (Blattman and Miguel 2010, Brückner and Ciccone 2010, Dixon 2009, Hegre and Sambanis 2006, Miguel et al. 2004, Weede 2004). Nevertheless, almost all studies note that there are few convincing theories that explain the ways these factors cause violence.

Many of the factors that increase the risk of civil war are sensitive to climate change. For example, there is robust evidence that climate change will slow rates of economic growth and impede efforts to grow per capita incomes, particularly in Africa where the risk of conflict is highest (chapter 10) (Eboli et al 2010, Mendelsohn et al. 2000, Mendelsohn et al. 2006, Stern 2007). Extreme events, which may become more intense due to climate change, can also produce economic shocks (Bergholt and Lujala, 2012; Hallegatte 2012; Adam, 2013), although the direct association between disasters and violent conflict is contested (Bergholt and Lujala 2012, Pelling and Dill 2010, Slettebak 2012). There is some evidence that under certain circumstances disasters can provide critical opportunities to build peace in conflict settings, and to improve governance institutions (Bruckner and Ciccone 2011, Kingsbury 2007, Olson and Gawronski 2010). There are theoretical reasons, but limited evidence, to suggest that climate change can lead to more inconsistent political institutions (Barnett and Adger 2007, Scheffran et al. 2012b).

In summary, there is justifiable common concern that climate change may increase the risk of violent conflict in certain circumstances (Bernauer et al. 2012; Gleditsch, 2012; Sceffran et al., 2012), even if the strength of the effect is uncertain. This concern is justified given robust knowledge of the factors that increase the risk of civil wars, and evidence that some of these factors are sensitive to climate change, There is also general agreement in the literature that there is a need for theories and data that explain the processes that lead from changes in climate to violence, including on the institutions that help avoid violent outcomes (Barnett and Adger, 2007; Sheffran and Battaglini, 2011; Buhaug and Theisen 2012, Gleditsch, 2012; Murtinho and Hayes, 2012;). However, confident statements about the effects of future changes in climate on violence of any kind are not possible given the absence of generally supported theories and evidence about causality (see Box 12-5).

12.5.2. Conflict and Insecurity Associated with Climate Policy Responses

Research is beginning to show that climate change mitigation and adaptation actions can increase the risk of violent conflict, as well as compound vulnerabilities in certain populations (Bumpus and Liverman 2008; Adger and Barnett 2009; Dabelko, 2009; Webersik 2010; Fairhead et al. 2012, Marino and Ribot, 2012,). There is evidence that violent political struggles occur over the distribution of benefits from natural resources (Peluso & Watts, 2001). On this basis, in circumstances where property rights and conflict management institutions are ineffective, efforts to mitigate or adapt to climate change that change the distribution of access to resources have the potential to create and aggravate violent conflict.

Actions taken in response to climate change can aggravate significant inequalities or grievances (Marino and Ribot, 2012), limit access to land and other resources required to maintain livelihoods, or otherwise undermine critical aspects of human security (Bumpus and Liverman 2008, Fairhead et al. 2012). Instances of maladaptation or greenhouse gas mitigation efforts at odds with local priorities and property rights increase the risk to populations and may increase the risk of conflict, particularly where institutions governing access to property are weak, or favour one group over another (Barnett and O'Neill, 2010; Butler and Gates 2012, McEvoy and Wilder, 2012).

Research on the rapid increase in biofuels finds evidence connecting "land grabbing," land dispossession, and social conflict (Molony and Smith 2010; Borras Jr. et al. 2010; Dauverge and Neville 2010; Vermeulen and Cotula 2010). Some research has identified links between increased biofuels production, food price spikes, and social instability such as riots (Johnstone and Mazo 2011).

The provision of financial resources in payment for ecosystem services projects such as are associated with Reduced Emissions from Deforestation and Forest Degradation (REDD) have the potential to stimulate violent conflicts (Melick 2010). For example, efforts to ensure 'REDD readiness' in Tanzania (Beymer-Farris and Bassett, 2012) and the Congo basin (Brown et al., 2011) have placed communities opposed to marginalization and displacement in conflict with conservationists and governments. Eriksen and Lind (2009) likewise find that climate change adaptation in Kenya has the capacity to aggravate surrounding conflicts.

Climate change mitigation will increase demand for deployment of less carbon-intensive forms of energy, including hydropower, some of which have historically resulted in social conflict and human insecurity (for example forced resettlement), and this is a basis for concerns about increased violence and insecurity in the future (Conca 2005; McDonald-Wilmsen et al., 2010; Sherbinin et al. 2011). Other research points to an increased use of nuclear power increasing the threat of nuclear proliferation or incidents of nuclear terrorism (Socolow and Glaser 2009).

12.5.3. Violent Conflict and Vulnerability to Climate Change

Many of the capacities required to adapt to climate change are threatened by the presence of ongoing or recent conflict (Barnett 2006, Brklacich et al., 2010). There is a strong body of evidence from development studies and political science that violent conflict undermines human security and the capacity of individuals, communities, and states to cope with changes (Stewart and Fitzgerald 2001; Blattman and Miguel 2010,). This evidence base suggests, with *high confidence*, that where violent conflict emerges and persists, capacity to adapt to climate change is likely to be low (as illustrated in Figure 12-2) (Barnett, 2006; Lind and Eriksen, 2006; Eriksen and Lind, 2009; Adger, 2010).

[INSERT FIGURE 12-2 HERE
Figure 12-2: Conflict and post-conflict societies exhibit low levels of governance and human development. Source: Adger (2010).]

There is some evidence that violent conflict degrades the quantity and quality of natural resources, and often leads to these resources being exploited inefficiently. Chronic political instability in Zimbabwe, is, for example implicated in high levels of illegal bush meat hunting (Lindsey et al., 2011). Conflict, and the displacement of large populations,

can also alter the abundance and distribution of biodiversity and can result in significant deforestation (Chase and Griffin, 2011; Lindsell et al., 2011; Stevens et al, 2011).

Violent conflict interrupts the ability of resource dependent individuals and communities to access natural resources (Pike, 2004; Detraz, 2009; Kolmannskog 2010; Raleigh, 2011), and in so doing limits their capacity to adapt to climate change. The denial of strategic space as a tactic in violent conflicts (through for example, deliberate destruction of crops and spreading of landmines in conflict affected regions) can reduce the capacity of individuals and communities to access natural capital (Berhe, 2007; Unruh, 2011).

Conflict disrupts markets and destroys infrastructure, limits education and the development of human capital, causes death and injury among a state's workforce, and decreases the ability of individuals, communities and the state to secure credit (Blattman and Miguel 2010, Goodhand, 2003; Stewart et al., 2001). Conflict thus creates poverty and constrains livelihoods which in turn increases vulnerability to the impacts of climate change (Nigel, 2009; Deng 2010a, Hilson and van Bockstael, 2011). Thus violent conflict is a major cause of hunger and famines (de Waal 1993, Messer and Cohen 2011, Rowhani et al., 2011).

The capacity for collective action is a critical determinant of the capacity to adapt to climate impacts, and this too can be undermined by violent conflict, depending on the nature of violence and the strategies households adapt in response (Deng, 2008 and 2010b). When conflict exacerbates existing horizontal inequalities between ethnic or religious groups, foments distrust in local or government institutions, or isolates individuals and households, capacities that are critical to coping with climate impacts are also degraded (Bogale & Korf, 2007). In situations where there is violent conflict, efforts to address climate change that provide financial or resource flows, or political levers that can be captured by local elites or illegitimate institutions, may compound divisions where such efforts (Brown et al., 2011; Verhoeven, 2011).

Conflict related displacement also creates and exacerbates social isolation and accompanying sources of vulnerability. Isolation from social networks can make it difficult to achieve pillars that underlie traditional livelihoods, such as marriage, access to land, or access to communal social safety nets in times of vulnerability (Raleigh, 2011; Kolmannskog 2010).

Violent conflict can decrease the capacity of local and state level institutions to function effectively (Feitelson et al., 2012; Tignino, 2011). For example, chronic political conflict has reduced the ability of governance institutions at many scales to manage water resources in the Gaza Strip effectively (Shomar, 2011), parts of the Balkans (Skoulikidis, 2009), and the Middle East (Zeitoun et al., 2012). Instability has affected planning process around urban land use in Palestine (Raddad et al., 2010) and traditional institutions for governing fishery rights in the Lake Chad Basin have been challenged by the presence of armed groups and illegal taxation systems sustained by non-legitimated government agents (Bene et al., 2003). Political instability has also been shown to contribute to poor urban governance in some regions of Iraq (Hassan, 2010).

Violent conflict may also undermine the ability of states to prevent and respond to natural disasters and humanitarian crisis (Keen, 2008). A lack of trust in government commitment or capacity to respond, the presence of police or military forces that lack legitimacy, or recent conflict between government and local forces, hampers the ability of these institutions to provide effective relief (Wisner, 2001).

12.5.4. Peace-Building Activities in Promoting Adaptation

It is widely established that resource management has significant potential to contribute to conflict management by channeling competing interests over resources into non-violent resolutions (Conca and Dabelko, 2002; Conca and Wallace 2009; Hammill and Matthew 2012). This research on environmental peacebuilding and peacemaking considers that natural resource management, and by extension climate change adaptation, can build peace to avoid conflicts, and broker peace in conflict situations.

Research on bilateral and multilateral interactions between two or more states from 1948 to 2008 shows evidence of significant formal cooperation among river basin riparian states, and no cases of water causing two states to engage in war (Wolf et al, 2003; De Stefano et al. 2010). Transboundary water cooperation, particularly joint management, flood control, and technical cooperation, can form a basis for longer-term cooperation on a range of contentious issues. Efforts at basin wide institutional development to lower conflict potential focuses on moving from the common assertion of rights to water to addressing the multiple values of water, and to sharing benefits across national boundaries (Sadoff and Grey 2002).

Beyond water, there is less evidence about the effectiveness of efforts to enhance cooperation and lower conflict around natural resources. Some transboundary conservation areas, referred to as 'peace parks', are designed to reduce conflict and enhance cooperation across borders. The evidence of the effectiveness of peace parks is limited and ambiguous, with some studies showing some evidence of political, economic and conservation cooperation (Ali and Marton-LaFevre, 2007), but also conflict generation between local communities, elites and states (Duffy 2002).

12.6. National Security Dimensions of Climate Change

Climate change will affect state security through mechanisms such as impacts on critical infrastructure, threats to territorial integrity, changing access to resources, or responses to climate change. State militaries are active in assessing and responding to these challenges (Dabelko, 2009). These infrastructure and geopolitical impacts directly affect state capacities to provide a range of ecological, economic, social, and political services that fundamentally contribute to human security (Barnett, 2003; Barnett et al., 2010; Webersik, 2010).

12.6.1. Critical Infrastructure and State Capacity

Climate change is expected to damage a range of critical infrastructure, with water and sanitation, energy, and transportation infrastructure posing especially severe vulnerabilities (Chapter 8; Rozenzweig et al., 2011; UN Habitat, 2011). Climate change is expected to exacerbate water supply problems in sensitive urban areas, to limit the ability to cool power plants, to increase energy demand beyond capacity in areas of high temperature increase, to disrupt power supply and telecommunications in areas of increased snow and ice storms, and to damage vital transportation infrastructure in areas subject to flooding and storm surge (see Chapter 8). Areas that are vulnerable to flooding and landslides will have greater risk of such infrastructure damage (Adelekan, 2010; Awuor et al., 2008; Revi 2005).

Climate change impacts on critical infrastructure will reduce the ability of some states to provide social and public services (see Chapter 8). For example, power outages stemming from water shortages or storms can in turn lead to reductions in service delivery on the part of hospitals, police forces and emergency response forces. Damage to roads, rails, airports, bridges and related transport infrastructure can similarly reduce the ability of governments to provide for citizen needs. Hughes et al. (2010) estimate a modest 1-2 percent additional investment costs to adapt water supply infrastructure to climate change, but with wide variation between countries. Thawing permafrost, for example, will affect water infrastructure but affect the whole viability of settlements and infrastructure in high latitude areas (Chapter 28; Larsen et al., 2008; Marino, 2012). In poorer countries or where economies depend heavily on climate-sensitive activities such as agriculture, climate impacts are expected to lead to significant declines in income and in turn government revenues. Mideksa (2010) estimates losses of nearly ten percent in Ethiopia GDP.

12.6.2. Geopolitical Issues

Analysis of the actions of states and security institutions show that many states view current and anticipated climate changes as contributing to geopolitical concerns (Dabelko 2009; Smith 2011). The ability of states to share resources and provide human security is challenged by climate change impacts. Climate change can create contested terrestrial

and marine territorial claims and in extreme cases can threaten the territorial integrity or viability of states (Barnett and Campbell, 2010; Houghton et al., 2010; Yamamoto and Esteban, 2010).

For small island states and countries with significant areas of soft low-lying coasts (Hanson et al., 2011) such as Bangladesh, Tanzania (Kebede and Nicholls, 2012), and Singapore (Ng and Mendelsohn, 2005) sea-level rise and extreme events threaten to erode and subsume significant land areas and associated infrastructure and settlements without significant adaptation investment (Chapter 5; Nicholls et al., 2011). For countries comprised entirely of low-lying atolls, sea-level rise, ocean acidification, and increases in episodes of extreme sea-surface temperatures, compromise human security for existing or larger numbers of people (Barnett and Campbell 2010, Fisher 2011). With projected high levels of sea-level rise beyond the end of this century, the physical integrity of low lying islands is under threat (Chapter 29, Houghton et al., 2010). The opening of resources, such as the social, economic and political dimensions of loss of sea ice in the Arctic (Chapter 28), represents an example of climate change impacts being geopolitically significant to states, even in the absence of direct conflict (Box 12-6).

Productive ocean fisheries are already directly affected by climate change, with loss of yields in the tropics, changing range of important commercial species in temperate regions, and greater variability in productivity and species composition in virtually all oceans (MacNeil et al., 2010). Fishing, as an economic activity often involves changing practices and locations, but the increased globalization of fisheries operations (Berkes et al., 2006) has been suggested to increase transboundary rivalry and threaten the sustainability of some fisheries (MacNeil et al., 2010).

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Box 12-6. Evidence on Security and Geopolitical Dimensions of Climate Change Impacts in the Arctic

Impacts of climate change on the Arctic region exemplify the multiple interactions of human security with geopolitical risks. System wide changes in the Arctic region affect multiple countries and a global commons resource given Arctic roles in regulating the global climate and ocean systems (Carmack et al., 2012; Duarte et al., 2012). Anticipated changes will contribute to greater geopolitical considerations and human insecurity in the Arctic region. They include: food insecurity affecting specific cultures and knowledge systems (outlined in Section 3); energy security implications through opening of sub-sea oil and gas reserves; increased shipping; and increased presence of militaries in the region.

Summer Arctic ice has had five of the lowest recorded minima in the period 2007-11 (Duarte et al., 2012), and projections of future loss suggest an ice-free Arctic ocean in summer by mid-century or before, with implications for land based infrastructure, shipping, coastal communities and transport (Holland et al., 2006; Stephenson et al., 2011; Larsen et al., 2008; See Chapter 28). There is only limited evidence on changes either creating or reviving terrestrial and maritime boundary disputes among Arctic countries (Borgerson, 2008; Lusthaus, 2010). Further, there is little evidence that the changing Arctic will become a site for violent conflict (Berkman, 2010; Brosnan et al., 2011; Young 2009; Young, 2012), given political institutions such as the Arctic Council are providing a forum for resolving resource sharing, new transportation practices, and boundary disputes. Research on livelihoods and cultural change dimensions of human security, however, also concludes that climate and ecological shifts will contribute significant challenges for adaptation (Nuttall, 2012; Hovelsrud et al., 2011b).

_____ END BOX 12-6 HERE _____

The impacts of climate-induced water variability on transboundary water basins constitute a cluster of geopolitical concerns. The high levels of international interdependence on transboundary rivers such as the Nile, Limpopo, Amu Darya, Syr Darya, Mekong, Ganges, Brahmaputra, and Indus connect the conditions of the rivers with national development trajectories. Climate change is anticipated to affect the timing and rate of flow of these rivers, contributing to concern over negative outcomes from additional stresses stemming from increased consumption and increased populations.

Research on transboundary conflict and cooperation prioritizes rate of change rather than absolute scarcity in connection with the risk of conflict over water, particularly between states (De Stefano et al. 2012). This focus stems from higher perceived risk of conflict when institutions at local, state, and regional levels have less time to adapt to scarcity or variability by dealing with disputes through diplomatic and other non-violent mechanisms (Wolf et al. 2003; De Stefano et al. 2010; De Stefano et al. 2012). Sudden changes in flow that heighten risk and challenge institutional responses include declines in seasonal snow or glacial melt. Transboundary basin institutions and international legal mechanisms have demonstrated the ability to lessen the likelihood of violent conflict (McCaffrey, 2000; Sadoff and Grey, 2002; Dellapenna and Gupta 2009; Tir and Stinnett, 2012;). Other research emphasize these transboundary water institutions receive limited financial and political investment, do not always include all riparians, and are present in only a limited number of transboundary basins (Conca et al., 2002).

Research on bilateral and multilateral interactions between two or more states from 1948 to 2008 shows significant formal cooperation among river basin riparian states while most interactions are low levels of cooperation and low levels of conflict (Wolf et al., 2003; De Stefano et al., 2010). Some find that the presence of a shared river basin is correlated with increased risk of state-to-state or dyadic conflict (Gleditsch et al., 2006), but the evidence suggests only a limited number of overtly violent conflicts between states and no cases of water causing two states to engage in formal war. Zeitoun and Warner (2006) and Zeitoun and Mirumachi (2008) distinguish between equitable and inequitable cooperation among transboundary riparians cooperating through joint water management institutions. Relative power differentials between countries, territories, or groups stemming from upstream or downstream position, economic power, or military power can undercut the wider conflict reduction impacts of formal institutional cooperation.

Geoengineering - intentional large-scale interventions in the earth system - either to reduce the sun's radiation that reaches the surface of the earth or to increase the uptake of carbon dioxide from the atmosphere (See Chapter 20), is increasingly considered a strategy to address climate change. The uncertainty and high likelihood of differential impacts of geoengineering (such as reduced precipitation in Asia (Ricke et al. 2011) with negative food production implications), are anticipated sources of tension or conflict between states (Robock 2008; Preston, 2013). The ability of states to unilaterally deploy geoengineering under limited international legal mechanisms creates the potential for conflict. A history of security institutions deploying geoengineering and weather modification presents the prospect of military involvement in climate change responses or reactions to them (Fleming, 2010). The degree of securitization of climate change is debated (Brzoska, 2012, add cites), but in the case of geoengineering, concern stems from possible dual use that potentially would violate the 1977 UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (Keith, 2000; Robock, 2008Corner and Pidgeon, 2010).

12.7. Synthesis

The evidence reviewed in this Chapter shows that climate change poses risks to various dimensions of human security, which arise through diverse causal processes, and which will be manifest at different scales. There is high agreement in the literature for this conclusion that comes from multiple lines of evidence. There are, however, multiple and competing perspectives on the nature and causes of insecurity arising from climate change (Barnett 2010). For example, farmers in the Sahel are concerned about the risks climate change poses to their livelihoods (Mertz et al. 2009), whereas people in Tuvalu report that the cultural impacts of migration are a primary concern (Mortreux and Barnett 2009). Organisations whose mandates include various aspects of human security also tend to focus on some risks of climate change over others. For example the International Council on Human Rights Policy is concerned with the risks climate change poses to human rights, the International Organization for Migration is concerned with the implications of climate change for migration, and the United States National Intelligence Council is focused on the risk climate change will increase political instability. In this respect the framing of climate change as an issue of human security facilitates conversations across the boundaries of diverse policy communities (Gasper 2010).

The risks that climate change poses to human security arise through multiple and interacting processes: those processes also operate across diverse spatial and temporal scales. High levels of complexity means that no

conceptual model or theory captures the full extent of the interactions between all of climate change, livelihoods, culture, migration and violent conflict. However, as this Chapter has shown, there are feedbacks between the key elements of livelihoods, culture, migration, and violent conflict. Figure 12-3 depicts interactions between the primary elements discussed in this Chapter. Deterioration in livelihoods, for example, is a human security issue in its own right, and also gives rise to migration, which may be adaptive, or unavoidable and undesirable: such movements in turn imply changes in important cultural expressions and practices, and, in the absence of institutions to peacefully manage the settlement of migrants in destination areas, can increase the risk of violent conflict. This conflict can in turn undermine livelihoods, impel migration, and weaken valued cultural expressions and practices. The evidence in the Sections above shows that some interventions and policies enhance human security, while others inadvertently can exacerbate insecurity (depicted in red and blue arrows in Figure 12-3).

[INSERT FIGURE 12-3 HERE
Figure 12-3: Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between elements. Examples of positive and negative changes in security associated with interventions indicated by arrows.]

A key finding of this Chapter is that institutions are integral to the risks climate change poses to all dimensions of human security. Again there is high agreement on this finding, with multiple lines of evidence from food security, to migration, to conflict resolution. The risks climate change poses to human security sometimes arise directly through interaction of material effects of changes in climate, through physical, biological and ultimately impacts in society. But evidence in this Chapter suggest that often the risks to human security also arise through ways in which institutions anticipate and react to these perceived or actual changes (Barnett et al. 2010; Ribot 2011; Artur and Hilhorst 2012). These institutional responses can significantly dampen or amplify the way changes in climate give rise to human insecurity (see Figure 12-3). For example, although declining productivity in crops and fisheries impacts on the food available to semi-subsistence farming and fishing households, anticipated or actual increasing scarcity on food markets also causes higher food prices, which can further undermine food security in those households (Chapter 7, and Badjeck et al., 2010; Downing 2002; Oluoko-Odingo 2011).

Adaptation and mitigation strategies can also dampen or increase human insecurity. With respect to both adaptation and mitigation strategies, there is an emerging consensus that those that are imposed on communities are more likely to impact negatively on human security than those that facilitate communities to respond in ways that are consistent with their capabilities and values (medium agreement, limited evidence) (Ensor and Berger, 2009; Barnett and O'Neill 2011, Marino 2012, Mercer et al. 2012). Adaptation strategies that seek to reduce exposure to climate change, through the development of large infrastructure or the resettlement of communities against their will, carry risks of disrupted livelihoods, displaced populations, deterioration of valued cultural expressions and practices, and in some cases violent conflict. Conversely, strategies such as the provision of microfinance, assistance to overcome barriers to mobility, and improving access to education and health care, enhance the ability of vulnerable populations to make and implement decisions that are consistent with their own capabilities and values. Hence such interventions are increasingly being shown to offset the adverse effects of climate change on livelihoods, unwanted migration, culture, and violent conflict. Similarly, mitigation policies that entail changes in property regimes that are not consistent with resource ownership and use can impact negatively on human security (Bumpus and Liverman 2008; Beymer-Farris and Bassett, 2012). There is as yet more limited evidence to demonstrate that mitigation activities that align with local interests and institutions can have co-benefits for human security, mitigation, and adaptation (Klein et al., 2005; Ayers and Huq, 2009; Laukkonen et al., 2009; Moser 2012).

Thus, climate change is not yet the primary risk to human security: it is one of many drivers of human security that vary in priority depending on location and circumstance. For regions where human insecurity is prevalent, these additional factors include poverty, discrimination, and inadequate provision of public services and public health, and opportunities for education. Investments in institutional responses to facilitate adaptation can dampen many of the potential adverse effects of climate change on human security (see Figure 12-3). Conversely, inappropriate climate policy responses may accelerate and amplify human insecurity.

There remains much uncertainty about the future impacts of climate change on human security. On the basis of current evidence about the observed impacts of climate change on environmental conditions, climate change will be

an increasingly important driver of human insecurity in the future (see Figure 12-3). At very high rates of projected warming, all of the aspects of human security discussed in this chapter will be adversely affected (for example in high latitude regions Box 12-6). At high rates of warming the rate of changes in environmental conditions in most places will be without any precedent in human history (New et al. 2011). Hence the evidence about the effects of past and present changes in climate on human security that informs much of the current literature on human security and climate change will be increasingly of diminishing value in analysing the human security implications of rapid or severe climate change.

Frequently Asked Questions

FAQ 12.1: How does lay knowledge of risks help adaptation to climate change?

Lay and traditional knowledge about the environment and climate are deeply rooted in history, and encompass important aspects of human life. Such knowledge is instrumental in shaping responses to climate change in all parts of the world. For many indigenous and local communities, for example, culture is constructed around livelihood activities, such as herding, hunting, fishing or farming. These cultural expressions include critical knowledge on dealing with highly variable environmental and societal conditions. Cultural perceptions of resilience to climate change, however, can either facilitate or hinder adaptation. Traditional knowledge is instrumental in developing community adaptation strategies and is increasingly seen a critical source for both scientific understanding of the consequences of climate change and for developing successful adaptation policies [12.3].

FAQ 12.2: How does migration contribute to adaptation to climate change impacts in vulnerable regions?

Patterns of migration are well established and primarily driven by economic factors: the dominant movement in the world is still from rural to urban areas within countries. Some migration flows are sensitive to changes in resource availability and ecosystem services and hence some rural to urban migration flows may be amplified by climate change impacts in developing and urbanizing countries. Migrants themselves may be vulnerable to climate change impacts, particularly in hazardous urban destinations. Given multiple motivations for all migration decisions, it is difficult to categorise any individual as a climate migrant [12.4].

FAQ 12.3: Will climate change cause war between countries?

Climate change has the potential to increase rivalry between countries over shared resources. For example, there is concern about rivalry over changing access to the resources in the Arctic and the future of transboundary rivers. Climate changes represent a challenge to the effectiveness of the diverse institutions that manage relations over these resources. However, there is high scientific agreement that this increased rivalry is unlikely to lead directly to warfare between states based on the evidence to date. That evidence shows that the nature of resources such as transboundary water and a range of conflict resolution institutions have able to divert rivalries in ways that avoid violent conflict [12.5 and 12.6].

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Table 12-1: Observed and projected impacts of climate variability and change on basic needs and livelihoods, and their role in undermining human security.

Dimensions of impacts		**Evidence from observations**	**Projections**
Deprivation of immediate basic needs	**Livelihood assets**	• Agricultural households faced with droughts have been observed to engage in environmentally destructive activities, such as reducing fallows, and increasing charcoal and timber production in Tanzania (Paavola 2008) • Household assets such as livestock may be disposed in times of crop failures: for example in the 1999/2000 drought in Ethiopia and the 1999-2004 drought in Afghanistan (Carter et al. 2007; de Weijer 2007). • Riverbank erosion associated with changed hydrological regimes causes loss of agricultural land (Paul and Routray, 2010). • Flooding is another source of crop failure	• Climate volatility is expected to increase with associated impacts on staple grains and an increase in poverty (Ahmed et al, 2009). • Changes in the viability of crops used to feed livestock will have an impact on the poor. In some locations maize yields are projected to decline substantially (Jones and Thornton, 2003). • Riverbanks may be further destabilized by environmental change and human interventions (Le et al, 2007) •
	Water stress and scarcity	• Glaciers and ice caps melts continue to affect water catchments downstream, leading to water stress and scarcity. • Example: glacial retreat of Mount Kilimanjaro is expected to bring acute problem of water scarcity particularly in the arid and semi-Arid regions of Africa (Kumssa and Jones 2011). • Glacier recession in the Cordillera Blanca in Peru is altering the hydrological regime with implications for local livelihoods and water availability in the arid coastal zone (Mark et al, 2010;	• Insecurity of water supply associated with climate change threatens the achievement of Millennium Development Goals to reduce the number people without sustainable access to safe drinking water (Hadipuro 2007). • The reduction in glacier extent and the associated loss of hydrological buffer is expected to increase (Vuille, 2008)
	Destruction of homes and properties	• Floods and related climate shocks destroy shelter and properties and curtail people's ability to meet basic needs. • Examples: A flood in Fiji (2009) brought economic losses of F$24 million affecting at least 25% of farm households (Lal 2010). • Sea level rise and increased frequency of extreme events rise the risk of loss of lives, homes, and properties and damages infrastructure and transport systems (Adrianto and Matsuda, 2002; Suarez et al. 2005; Philips and Jones 2006; Ashton et al. 2008; Von Storch et al. 2008).	• In the Netherlands, the total amount of urban area that can potentially be flooded has increased six-fold during the 20th century and may double again during the 21st century (de Moel et al., 2011). • In England and Wales, projected changes in flood risk mean economic damages may increase up to 20 times by the 2080s (Hall et al. 2003).

Erosion of livelihood and human capabilities	**Agriculture and food security**	• Interaction of climate change with poverty and other political, social, institutional and environmental factors adversely affects agriculture production and exacerbates the problem of food insecurity (Downing 2002; Trotman et al. 2009; Saldana-Zorrilla 2008; Kumssa and Jones 2011). • Examples: most of the studies focus in Africa, due to its dependence on rain-fed agriculture (Kumssa and Jones 2011; in Kenya, Oluoko-Odingo 2011; in Southern Africa, Drimie and Gillespie 2010; in Zimbabwe and Zambia (Mubaya et al. 2012).	• Studies of African agriculture using various climate scenarios indicate that increasing temperature and rainfall variation have serious impacts on crops and livestock production that are likely to lead to increased poverty, vulnerability and loss of livelihoods. • Examples: Ethiopia (Deressa and Hassan 2009); Kenya (Kabubo-Mariara 2009); Burkina Faso, Egypt, Kenya and South Africa (Molua et al. 2010); and sub-Saharan Africa (Jones and Thornton 2009). • Livelihood insecurity among small-scale rain-fed maize farmers in Mexico is predicted due to potential loss of traditional seed sources (Bellona et al. 2011).
	Human capital	Health: • Food shortage, absence of safe and reliable access to clean water and good sanitary conditions, and destruction of shelters and displacements, all have negative bearing on human health (Costello et al. 2009) • Poor nutrition combined with mental health conditions after a disaster can lead in the long run to erosion of human capability (Costello et al. 2009)	Health: • A comparative analysis of African and non-African countries using an 'income-climate trap model' that explains the multi-directional interaction between income, climate and life expectancy, reveals that climate is important in determining both life expectancy and income. • Climate change is likely to worsen localized conditions that could see many less developed countries, particularly from Africa, sinking deeper into an income-climate trap of underdevelopment in health (Tang et al. 2009). • Analysis of the economic and climatic impacts of three emission scenarios and three tax scenarios, estimates the impacts on food productivity and malaria infection to be very severe in some Asian countries (Kainuma et al. 2004).
		Education: • Droughts and floods can intensify the pressure to transfer children to the labour market (Ethiopia and Malawi, UNDP 2007). • - Indian women born during a drought or flood in the 1970s were 19 percent less likely to ever attend primary school, when compared with women of the same age who were not affected by natural disasters (UNDP 2007).	Loss of lives: • Studies of the impacts of future floods using a combination of socio-economic and climate change scenarios for developed countries predict an increase in fatalities. • Example: In the Netherlands, sea level rise combined with other factors potentially increases the number of fatalities four times (Maaskant et al. 2009)

Table 12-2: Cultural dimensions of human security in the context of climate change.

Core climate change dimensions	**Cultural dimensions**	**Role in shaping HS (facilitating - hindering adaptation, action, response)**	**References**
Climate science and policy	Framing of climate change in a dominant language (English) Global climate change policy developments	How concepts and uncertainties are translated, imported and incorporated facilitate or hinder adaptation; Available explanatory tools facilitates adaptation; Successful translation of climate change impacts facilitates adaptation; Lack of trust in science and in policy hinder adaptation; Policy and decision-making that is inclusive of cultural perspectives increases security; Policy not recognizing the connection between nature and culture hinders adaptation; Awareness of culture facilitates adaptation	Ifejika Speranza *et al.*, 2008; Stadel, 2008; Jacka, 2009; Bogale and Korf, 2009; Green, *et* al., 2010; Burch, 2010; Schroeder, 2010; Osbahr *et al.*, 2010; McNeely, 2011; Gero *et al.*, 2011; Sánchez-Cortés and Chavero, 2011; Roncoli, et al, 2011; Kuruppu and Liverman, 2011; Rudiak-Gould 2012
Impacts of environmental conditions and extreme events and changing natural resource base	Elements of cosmology such as: World views Coupling of nature-culture Power relations Heterogeneity within groups and communities	New technologies may facilitate adaptation; Livelihood diversification and flexibility facilitate adaptation; Limitations of local knowledge hinder adaptation; Narratives and history about past changes and current conditions may drive adaptation; Erosion of cultural core may decrease human security; Institutional responses and resource management will impact human security; Co-management of resources increases adaptive capacity; Lack of awareness and understanding of culture constrains action and hinders adaptation; Knowledge and cultural repertoire limited for responding to new challenges will hinder adaptation; Perceptions of resilience may hinder or facilitate adaptation;	Nunn, 2000; Seixas and Berkes, 2003; Davidson *et al.*, 2003; Desta and Coppock, 2004; Herbert, 2005; Zamani *et al*., 2006; Ford *et al.*, 2006, 2008; Crona, 2006; Aguilar *et al.*, 2009; Kuruppu and Liverman 2011, Rudiak-Gould, 2012; Roncoli *et al*., 2011; Gearheard *et al*., 2010; Hovelsrud and Smit, 2010; Nyong *et al.*, 2007; Tyler *et al.*, 2007; Angassa and Oba, 2008; Osbahr *et al.*, 2010; Lefale, 2010 Crate, 2008; Gregory and Trousdale, 2009; Harries and Penning-Rowsell, 2011; Gero *et al.*, 2011; Fazey *et al.*, 2010; Furgal and Seguin, 2006; Sudmeier-Riuex *et al.*, 2012; Anik and Khan, 2012; Kuhlicke, 2010; Valdivia *et al.*, 2010; Kesavan and Swaminathan, 2006; Jacka, 2009; Pearce *et al.*, 2010; Adler, *et al*., 2012; Gómez-Baggethun *et al*., 2012; Burningham *et al.*, 2008; West and Hovelsrud, 2010; Nursey-Bray *et al*., 2012; Armitage *et al.*, 2011; Dumaru, 2010; King, 2008; Nielsen and Reenberg, 2010; Onta and Resurrection, 2011; de Sherbinin *et al.*, 2008; Kalikoski *et al.*, 2010; Hovelsrud *et al.*, 2010a,b; Rybråten and Hovelsrud, 2010; McNeeley, 2011; Marshall 2011; Berkes and Armitage, 2010; Ford and Goldhar, 2012; Eakin *et al*., 2012;
Scientific observations monitoring, models, projections, scenarios	Local, traditional and indigenous knowledge through observations and experience	Mutual integration of traditional, local and scientific knowledge may facilitate adaptation and strengthen human security; Climate projections with local relevance will facilitate adaptation; Knowledge included in climate policy and decision making decreases risks and increases human security: Intergenerational knowledge transfers facilitate adaptation; Knowledge not included in adaptation planning decreases human security	Orlove *et al.*, 2000, 2010; Ingram *et al.*, 2002; Tàbara *et al.*, 2003; Alcántara-Ayala et al., 2004; Gearheard *et al*., 2010; Roncoli, 2006; Forbes, 2007; Anderson *et al.*, 2007; Vogel *et al.*, 2007; Nyong *et al.*, 2007; Tyler *et al.*, 2007; Catto and Parewick, 2008; Frazier *et al.*, 2010; Marfai *et al.*, 2008; Mercer *et al.*, 2009; Pearce *et al.*, 2009; Marin, 2010; Mark *et al.*, 2010; Smit et al 2010; Burns *et al.*, 2010; Hovelsrud and Smit, 2010; Kalanda-Joshua et al., 2011; Flint *et al*., 2011; Ravera *et al.*, 2011; Sánchez-Cortés and Chavero, 2011; Huntington, 2011; Eira *et al.*, 2013.

Table 12-3: Empirical evidence on observed or projected mobility outcomes (migration, immobility, or displacement) associated with weather-related extremes or impacts of longer-term climate change.

	Drought and land degradation
Evidence for increasing migration, mobility or increased displacement.	↑ Ethiopia: Outmigration of household heads due to drought related famine, although different coping strategies lead to variations in the timing of migration (Meze-Hausken, 2000). ↑ Mexico: Increased propensity to migrate to the United States related to years with negative crop productivity (Feng et al., 2010) ↑ Western Sahara: Droughts play a crucial role in patterns of international migration from refugee camps (Gila et al., 2011). ↑ Kenya: Households farming high quality soil are less likely to migrate, especially temporary labour migration (Gray, 2011). ↑ India: Temporary migration identified as 'the most important' coping strategy in times of drought in rural villages (Jülich, 2011). ↑ Burkina Faso: Simulations of dry climate scenario produces increased migration fluxes compared to wet scenarios. Highest international migrant flows are shown with the dry climate scenarios (Kniveton et al., 2011). ↑ Canada: Higher population loss associated with settlements containing areas of poorer quality agricultural soils during droughts of 1930s (McLeman and Ploeger 2011). ↑ Guatemala: Outmigration was commonly attributed to soil degradation, resulting in migration to the expanding agricultural frontiers by open forests (López-Carr, 2012). ↑ Sahel: In three case regions, the pressure to migrate significantly increased since the 1970s possibly as a response to the onset of the persistent droughts. (Scheffran et al., 2012b; 2012c).
Evidence for decreased migration, mobility or significantly trapped populations.	↓ Mali: Reduced international migration during 1980s drought and an increase in cyclical migration (Findley, 1994). ↓ Nepal: Deforestation, population pressure and agricultural decline leads to local mobility, especially among women, but no increases in internal or international migration (Massey et al., 2010; Bohra-Mishra and Massey, 2011) ↓ Uganda: High soil quality marginally increases migration, especially permanent non-labor migration. (Gray, 2011).
Evidence for socially-differentiated mobility outcomes.	⇅ Burkina Faso: Land degradation is associated with less first time migration, but more migration for previous migrants. Land degradation greater influence on migration than rainfall variability (Henry et al., 2004). ⇅ Burkina Faso: Drier region populations more likely to migrate than people from regions with more rainfall. Rainfall deficits have different impacts depending on the duration and distance of the migration (Henry et al., 2004). ⇅ United States: Dustbowl migrants from Oklahoma to California in the 1930s had different social and economic capital endowments to those who stayed within state (McLeman and Smit, 2006). ⇅ Ecuador: Influence of natural capital on migration differed between men and women. Access to land facilitates migration in men; women are less likely to migrate from environmentally degraded areas (Gray, 2010). ⇅ Ethiopia: Male migration increases with drought. However, marriage related moves by women decrease with drought. (Gray and Mueller, 2012). ⇅ Burkina Faso: Labour migration became a key off-farm livelihood strategy after droughts in the 1970s for those groups dependent on rain-fed agriculture. However, those with large cattle herds relied on livestock sales as a coping strategy with negative implications for future resilience (Nielsen and Reenberg, 2010). ⇅ Mongolia: Diversity in herders' mobility strategies to mobility in response to climate change. For a minority, responses entailed greater overall annual mobility. Other herding households experienced significant reductions in mobility (Upton, 2012). ⇅ Tanzania: Agent based models concluded the normalised rate of need-driven migration was greatest under extreme drying, whereas aspirational migration was less sensitive to changes in rainfall (Smith et al., 2013).

	Flooding	
Evidence for increasing migration, mobility or increased displacement.	↑	USA: counties and parishes in Louisiana of the 77 impacted counties experienced 82% of the total population increase in the year following Hurricane Katrina (Frey and Singer, 2006).
	↑	Vietnam: Cumulative impacts of seasonal flooding increases outmigration rates in the Mekong Delta (Dun, 2011).
	↑	Bangladesh: 22% of households affected by tidal-surge floods, and 16% affected by riverbank erosion, moved to urban areas. (Penning-Rowsell et al., 2013).
Evidence for decreased migration, mobility or significantly trapped populations.	↓	Bangladesh: No out-migration detected after 2004 tornado in Bangladesh as a result of the effective distribution of disaster aid (Paul, 2005).
	↓	Senegal: Over 40 percent of new migrant populations located in high risk flood zones in Dakar (Quoted in Black et al., 2011b).
Evidence for socially-differentiated mobility outcomes.	⇅	USA: Emergency evacuation responses and return migration after the event highly differentiated income, race, class and ethnicity (Elliott and Pais, 2006; Falk et al., 2006; Landry et al., 2007).
	⇅	Bangladesh: Wide variation among groups in attitudes and capabilities for migration as an adaptation to the impact of cyclone Aila (Kartiki, 2011)

	Sea level rise	
Evidence for increasing migration, mobility or increased displacement.	↑	United States: Underlying driver of sea level rise caused initial depopulation. Final abandonment was a result of the population falling below levels to support local community services. (Arenstam Gibbons and Nicholls, 2006).
	↑	Vanuatu: Whole village displacement associated with inundation, both from sea level rise and tectonic movement on Torres Islands (Ballu et al., 2011).
	↑	United States: The impact of future sea-level rise will extend beyond the inundated counties through migration networks that link inland and coastal areas and their populations (Curtis and Schneider, 2011).
	↑	Papua New Guinea: Population considering resettlement on Bougainville to the main island due to coastal erosion, land loss, saltwater inundation and food insecurity (Oliver-Smith, 2011).
	↑	United States: Coastal villages in Alaska affected by sea-level rise and coastal erosion. The population as Shishmaref have decided to relocate (Oliver-Smith, 2011; Marino, 2012).
Evidence for decreased migration, mobility or significantly trapped populations.	↓	Tuvalu: On the island of Funafuti, climate change is not a cause for concern nor cited as a reason for migration (Mortreux and Barnett, 2009).

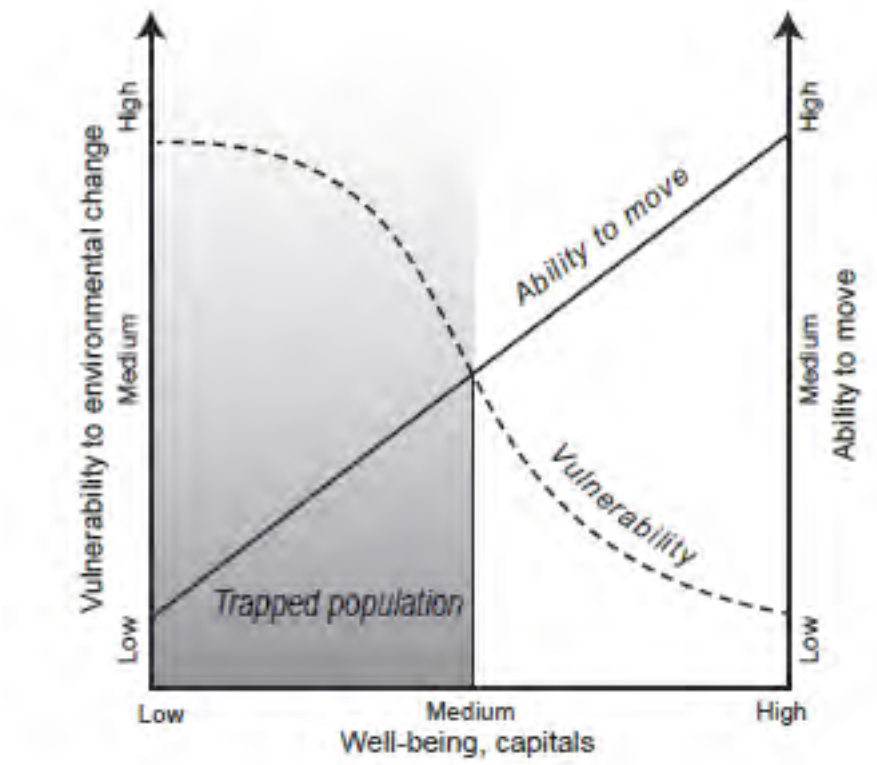

Figure 12-1: Relationship between vulnerability to environmental change and mobility. Lack of mobility and high vulnerability are positively correlated. Adapted from Black et al. (2013).

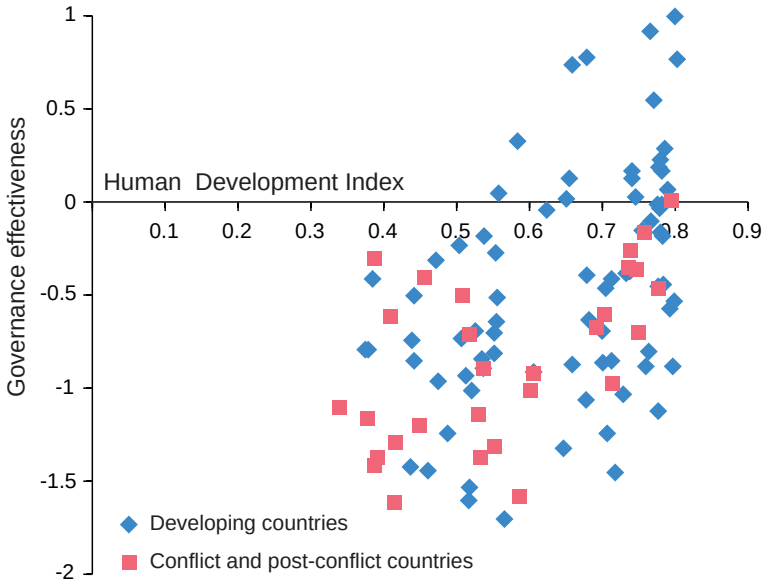

Figure 12-2: Conflict and post-conflict societies exhibit low levels of governance and human development. Source: Adger (2010).

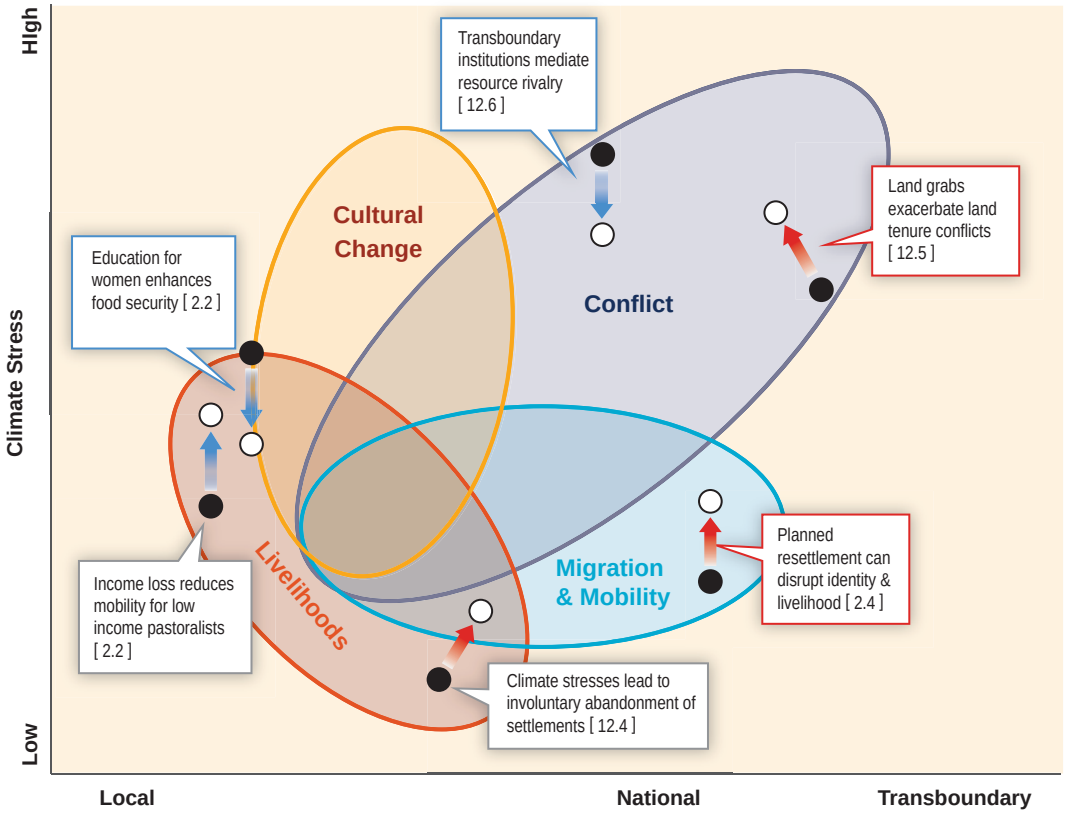

Figure 12-3: Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between elements. Examples of positive and negative changes in security associated with interventions indicated by arrows.

Chapter 13. Livelihoods and Poverty

Coordinating Lead Authors
Lennart Olsson (Sweden), Maggie Opondo (Kenya), Petra Tschakert (USA)

Lead Authors
Arun Agrawal (USA), Siri Eriksen (Norway), Shiming Ma (China), Leisa Perch (Barbados), Sumaya Zakieldeen (Sudan)

Contributing Authors
Catherine Jampel (USA), Valentina Mara (Romania), Andrei Marin (Norway), David Satterthwaite (UK), Asuncion St. Clair (Norway), Andy Sumner (UK)

Review Editors
Susan Cutter (USA), Etienne Piguet (Switzerland)

Volunteer Chapter Scientist
Anna Kaijser (Sweden)

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Executive Summary

This chapter discusses how livelihoods, poverty and the lives of the poor, and inequality interact with climate change, climate variability, and extreme events in multifaceted and cross-scalar ways. It examines how current impacts of climate change, projected impacts up until 2100, and climate change responses affect livelihoods and poverty. The Fourth Assessment Report stated that the socially and economically disadvantaged and marginalized are disproportionally affected by climate change. Yet, climate change is rarely the only factor that affects livelihood trajectories and poverty dynamics; it interacts with a multitude of non-climatic factors, which makes detection and attribution challenging.

Climate change constitutes an additional burden to the rural and urban poor. It acts as a threat multiplier, often with negative outcomes for livelihoods (*very high confidence, based on robust evidence, high agreement*).

- Weather events and climate, ranging from subtle shifts in trends to extreme events, affect poor people's lives directly through impacts on livelihood assets, such as losses in crop yields, destroyed homes, food insecurity, and loss of sense of place, and indirectly through increased food prices and climate policies. [13.2.1, 13.3]
- Changing climate trends provoke shifts in rural livelihoods such as from crop-based to mixed livestock- and forest-based livelihoods or to wage-based labor in agricultural and urban employment. [13.2.1.2]
- Urban and rural transient poor who face multiple deprivations slide into chronic poverty as a result of weather events or extreme events, or a series of events, when they are unable to rebuild their eroded assets (*limited evidence, high agreement*) [13.2.1.3]
- Many weather events that affect poor people remain unrecognized, such as short periods of extreme temperature or minor changes in the distribution of rainfall, due to short time series and geographically sparse, aggregated, or partial data, inhibiting detection and attribution in many low-income countries. [13.2.1]

Climate change worsens existing poverty, exacerbates inequalities, and triggers new vulnerabilities and some opportunities. Poor people are poor for different reasons and thus are not all equally affected, and not all vulnerable people are poor. Climate change interacts with non-climatic stressors and entrenched structural inequalities to shape vulnerabilities (*very high confidence, based on robust evidence, high agreement*).

- Socially and geographically marginalized people exposed to persistent inequalities at the intersection of gender, age, race, class, caste, indigeneity, and (dis)ability are particularly negatively affected by weather events and climate. Context-specific conditions of marginalization shape differential vulnerability. [13.1.2.5]
- Preexisting gender inequalities are increased or highlighted by weather events and climate. Gendered impacts depend on customary and new roles in society, often entailing higher workloads, occupational hazards indoors and outdoors, psychological and emotional distress, and mortality in climate-induced disasters. [13.2.1.5]

- Very scarce evidence exists that demonstrates positive impacts of climate change on the poor, including flood preparedness, collective action, institutional change, and social asset accumulation. Often, the more affluent can better take advantage of shocks and crises, given their flexible assets and power status. [13.1.3, 13.2.1.4]

Climate change will create new poor, in low-income countries and middle- to high-income countries and jeopardize sustainable development. Most severe impacts are projected for urban areas and some regions in sub-Saharan Africa and Southeast Asia (*medium confidence, based on medium evidence, medium agreement*).

- Future impacts of weather events and climate will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas. [13.2.2.4, 13.4]
- Climate change will exacerbate multidimensional poverty in low and lower middle-income countries, including high mountain states and countries with indigenous people threatened by sea level rise and relocation, and create new poverty pockets in upper middle- to high-income countries. [13.2.2]
- Urban and wage-labor dependent poor households, as well as regions with high food insecurity, above all in Africa, and high inequality, will be particularly affected due to food price increases. [13.2.2.3, 13.2.2.4]

Policy responses for climate change mitigation or adaptation will result in mixed and potentially detrimental outcomes for poor and marginalized people (*medium confidence, based on low evidence, high agreement*).

- Mitigation efforts such CDM and REDD+, as well as land acquisition for food and biofuel production, show preliminary negative impacts on the poor, particularly indigenous people and (women) smallholders. [13.3.1]
- Insurance schemes, social protection programs, and disaster risk reduction may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty. [13.3.2.2, 13.4.1]
- Climate-resilient development pathways will have only marginal effects on poverty reduction, unless structural inequalities are removed and needs for equity among the poor and non-poor met. [13.3.1, 13.4.2]

13.1. Scope, Delineations, and Definitions: Livelihoods, Poverty, and Inequality

Understanding the impacts of climate change on livelihoods and poverty requires examining the complexities of poverty and the lives of the poor and non-poor as well as the multifaceted and cross-scalar intersections of poverty and livelihoods with climate change. This chapter examines these complexities. First, it presents the concepts of livelihoods, poverty, and inequality, and their relationships to each other and to climate change. Second, it describes observed impacts of weather events and climate on livelihoods and poverty and impacts for 2015-2100 for the urban and rural poor. Third, it discusses impacts of climate change mitigation and adaptation responses on livelihoods and poverty. Finally, it outlines implications for poverty alleviation efforts and climate-resilient development pathways.

Livelihoods and Poverty is a new chapter in the AR5. Although the AR4 WGII contributions mentioned poverty, as one of several non-climatic factors contributing to vulnerability, as a serious obstacle to effective adaptation, and in the context of endemic poverty in Africa (Technical Summary, Chapters 7, 8, 18, 20), no systematic assessment was undertaken. Livelihoods were more frequently addressed in the AR4, predominantly with reference to livelihood strategies and opportunities, diversification, resource-dependent communities, and sustainability, yet a coherent livelihood lens for assessing impacts was lacking. This chapter addresses these gaps and how climate change intersects with other stressors to shape livelihood choices and trajectories, affect the spatial and temporal dimensions of poverty dynamics, and reduce or exacerbate inequalities given differential vulnerabilities.

13.1.1. Livelihoods

Livelihoods (see also Glossary) are understood as the ensemble or opportunity set of capabilities, assets, and activities that are required to make a living (Chambers and Conway, 1992; Ellis *et al.*, 2003). They depend on access to natural, human, physical, financial, social, and cultural capital (assets); the social relations people draw upon to combine, transform, and expand their assets; and the ways people deploy and enhance their capabilities to be, act, and make lives meaningful (Scoones and IDS, 1998; Bebbington, 1999). Livelihoods are dynamic and people adapt to and change with internal and external stressors. Ultimately, successful livelihoods transform assets into income, dignity, and agency, to improve living conditions, a prerequisite for poverty alleviation (Sen, 1981).

Livelihoods are universal. The poor and the rich both pursue livelihoods to make a living. However, the adverse impacts of weather events and climate increasingly threaten and erode basic needs, capabilities, and rights, particularly among poor and disenfranchised people, in turn shaping their livelihoods (UNDP, 2007; Leary *et al*., 2008; Adger, 2010; Quinn *et al*., 2011). Some livelihoods are directly climate-sensitive, such as smallholder agriculture, seasonal employment in agriculture (e.g. tea, coffee, sugar), fishing, pastoralism, and tourism. Climate change also impacts households dependent on informal livelihoods or wage labor in poor urban settlements, directly through unsafe settlement structures or indirectly through rises in food prices.

13.1.1.1. Dynamic Livelihoods and Trajectories

A livelihood lens allows for a multidimensional and grounded analysis of people's complex lives by recognizing the flexibility and constraints with which they construct and adapt their livelihoods, and their dynamic decision making under climatic and other stressors. Livelihood analyses focus on the wider institutional, cultural, and policy contexts as well as shocks, seasonality, and trends, including processes that force poor and vulnerable people onto undesirable trajectories or toward enhanced wellbeing. Better infrastructure and technology as well as diversification of asset and activity portfolios and social support capabilities can boost livelihoods, spreading risks and broadening opportunities (Batterbury, 2001; Ellis *et al*., 2003; Clot and Carter, 2009; Carr, 2013). The sustainable livelihoods framework (Chambers and Conway, 1992) is the most widely-used approach for identifying how specific strategies may lead to cycles of livelihood improvements or impoverishment and critical thresholds beyond which certain livelihoods are radically transformed (Sabates-Wheeler *et al*., 2008). Yet, it has been criticized for not sufficiently explaining the wider structural processes that constrain livelihoods and wellbeing (Scoones, 2009).

13.1.1.2. Multiple Stressors

Livelihoods rarely face only one stressor or shock at a time. The literature emphasizes the synergistic relationship between weather events and climate and a variety of other environmental, social, and political stressors; jointly, they impinge on livelihoods and reinforce each other in the process, often negatively (Reid and Vogel, 2006; Schipper and Pelling, 2006; Tschakert, 2007; IPCC, 2007; Morton, 2007; Easterling *et al*., 2007; O'Brien *et al*., 2008; Eakin and Wehbe, 2009; Eriksen and Silva, 2009; Ziervogel *et al*., 2010). "Double losers" may emerge from simultaneous exposure to climatic change and other stressors such as economic globalization, rapid urbanization, and the spread of infectious diseases, further marginalizing vulnerable groups (O'Brien and Leichenko, 2000; Eriksen and Silva, 2009). Climatic and other stressors affect livelihoods at different scales: the level of spatial (e.g., village, nation) or temporal (e.g., annual, multi-annual) analysis affects detection and attribution of impacts. Impacts, both direct and indirect, are often amplified or weakened at different levels. Global or regional processes interact with local and national processes, often mediated by institutions, to generate locally experienced stressors and shocks (Reid and Vogel, 2006; Thomas *et al*., 2007; Paavola, 2008; Pouliotte *et al*., 2009) (see Figure 13-5 within FAQ 13.2).

Multiple stressors, simultaneous and in sequence, differentially shape livelihood dynamics and trajectories based on inequalities and differential vulnerabilities. More affluent households may be able to capitalize on shocks and crises while poorer households with less flexible opportunity sets are forced to erode their asset bases. Some coping strategies and limited ability to adapt may result in adverse consequences. Such maladaptive actions (see Glossary, Chapters 14, 16) undermine the long-term sustainability of livelihoods and results in downward trajectories, further impoverishment, and poverty traps (Ziervogel *et al*., 2006; Tanner and Mitchell, 2008; Barnett and O'Neill, 2010).

13.1.2. Dimensions of Poverty

Poverty is a complex concept with conflicting definitions and considerable disagreement in terms of framings, methodologies, and measurements. Despite differences in approaches emphasizing distinct aspects of poverty at the individual or collective level, such as income, capabilities, and quality of life (Laderchi *et al*., 2003), poverty is now recognized as multidimensional (UNDP, 1990). Poverty is influenced by social, economic, institutional, political,

and cultural drivers; reversing it requires efforts in multiple domains by promoting opportunities and empowerment, and enhancing security (World Bank, 2001). In addition to material deprivation, poverty considers agency and identity, and a sense of belonging and socio-cultural heritage (O'Brien and Leichenko, 2003). The AR4 identified poverty as "the most serious obstacle to effective adaptation" (Confalonieri *et al*., 2007, p.417).

13.1.2.1. Framing and Measuring Multidimensional Poverty

Over the last six decades, conceptualizations of poverty have become increasingly broader, poverty measurements more multifaceted, and spatial and temporal analyses more nuanced. Attention to multidimensional deprivations – hunger, illiteracy, unclean drinking water, lack of access to health services and electricity, and social isolation (WHO, 2006) – has shifted the analytical lens to the dynamics of poverty and its institutionalization within social and political norms. However, given these shifting conceptualizations over time, reliable measurement remains challenging. This, in turn, complicates attribution of climate change impacts and responses on the world's poor.

In climate change literature, poverty and poverty reduction have been predominantly defined through an economic lens, reflecting various growth and development discourses (Hirschman, 1988; Sachs, 2006; Collier, 2007). Less attention has been paid to relational poverty, produced through material social relations and in relation to privilege and wealth (Sen, 1976; Mosse, 2010; Alkire and Foster, 2011; UNDP, 2011a; Chen and Ravallion, 2012). Yet, such framing allows for addressing the social and political contexts that generate poverty and vulnerability to climate change (McCright and Dunlap, 2000; Bandiera *et al*., 2005; Leichenko and O'Brien, 2008). Many climate policies to date favor market-based responses using sector-specific and economic growth models to counter trends that may slow down the achievements of the 2000 Millennium Development Goals (MDGs). For instance, the World Bank encourages "mitigation, adaptation, and the deployment of technologies" that "allow[s] developing countries to continue their growth and reduce poverty" (World Bank, 2010, p.257). A relational approach highlights the integral role of the poor in all social relations (Pogge, 2009; O'Brien *et al*., 2010; Gasper, 2010; UNRISD, 2010; St.Clair and Lawson, 2013), challenging earlier constructions of the poor as an underclass, undeserving, and with inadequate moral values (O'Connor, 2002; Mosse, 2010). It also emphasizes equity, human security, and dignity (UNRISD, 2010; Deacon and Cohen, 2011; Haarstad and St Clair, 2011). Akin to the capabilities approach (Sen, 1985; Sen, 1999; Nussbaum, 2001; Alkire, 2005; Nussbaum, 2011), the relational approach stresses the needs, skills, agency, and aspirations of poor people while tackling structural causes of poverty, inequalities, and uneven power relations.

The IPCC AR4 (Yohe *et al*., 2007) highlighted that – with *very high confidence* – climate change will impede nations' ability to alleviate poverty and achieve sustainable development, as measured by progress towards the MDGs. Empirical assessments of the impact of climate change on MDG attainment are limited (Fankhauser and Schmidt-Traub, 2011), and the failure to reach these goals by 2015 has significant non-climatic causes (e.g. Hellmuth and IRI, 2007; UNDP, 2007). To date, global indicators for seven out of the eight MDGs, including income poverty, have improved since 1990. However, at a country level, only half of all countries are on track for income poverty reduction. The 2010 UNDP Multidimensional Poverty Index, measuring intensity of poverty based on patterns of simultaneous deprivations in basic services (education, health, and standard of living) and core human functionings, states that 1.7 billion people are multidimensionally poor, a far higher number than the 1.29 billion (World Bank, 2012a) indicated by the income-centered International Poverty Line (IPL) set at $1.25/day.

[INSERT FIGURE 13-1 HERE
Figure 13-1: Multidimensional poverty and income poverty, with linear regression relationship (dotted line) and shaded 95% confidence interval based on 96 countries (HDR, 2011). The map inset shows the Poverty Gap Index score in Viet Nam, aggregated at district level, expressed as ratio of poverty line of yearly expenditure per capita).]

13.1.2.2. Geographic Distribution and Trends of the World's Poor

Geographic patterns of poverty are uneven and shifting. In 1990, most of the world's $1.25 poor (93%) lived in low-income countries (LICs). By 2008, the majority of the poor (>70%) resided in lower and upper middle-income countries (LMICs and UMICs), in part because some LICs such as India, Nigeria, and Pakistan evolved to MIC

status. To date, one billion people live under $1.25/day in MICs and a second billion between $1.25 and $2, with an additional 320m and 170m in the LICs, respectively. Of the approximately 2.4 billion living under $2/day, half live in India and China. By 2020, 60-80% of world poverty at $1.25and 40-55% at $2 will be concentrated in sub-Saharan Africa with the rest in South Asia (Sumner, 2010; Sumner *et al*., 2012). Using the $1.25/day poverty line suggests that at least 70% of the poor live in rural areas in developing countries (IFAD, 2011), despite worldwide urbanization. Yet, this poverty line considerably understates urban poverty since it overlooks the high costs of food and non-food needs in many urban contexts (Mitlin and Satterthwaite, 2013). Estimates of poverty by use of national accounts means (see Chapter 19) suggest low poverty levels by 2025 as these estimates project $2 poverty to be eliminated in large MICs such as India and Indonesia, whereas surveys means (e.g. Chen and Ravallion, 2012; Sumner *et al*., 2012; Sumner, 2012a) project a $2 poverty split between current LICs and MICs at least until 2030.

This shift in distribution of global poverty toward MICs challenges the orthodox view that most of the world's extreme poor live in the poorest countries, and suggests that substantial pockets of poverty can persist in areas with higher levels of average per capita income. Understanding the shift in the geography of poverty is vital for attributing climate change impacts on poverty. For example, both climate finance and research focusing on climate impacts and vulnerabilities are largely directed towards LICs. Less attention is paid to the poor in MICs and HICs, where poverty and income inequality are rising (OECD, 2011; Gower *et al*., 2012).

13.1.2.3. Spatial and Temporal Scales of Poverty

Poverty is also socially distributed, across spatial and temporal scales. Not everybody is poor in the same way. Spatially, factors such as access to and control over resources and institutional linkages from individuals to the international level affect poverty distribution (Anderson and Broch-Due, 2000; Murray, 2002; O'Laughlin, 2002; Rodima-Taylor, 2011). Even at the household level, poverty differs between men and women and age groups, yet data constraints impede systematic intra-household analysis (Alkire and Santos, 2010). The distribution of poverty also varies temporally, typically between chronic and transient poverty (Sen, 1981; Sen, 1999). Chronic poverty describes an individual deprivation, per capita income, or consumption levels below the poverty line over many years (Gaiha and Deolalikar, 1993; Jalan and Ravallion, 2000; Hulme and Shepherd, 2003). Transient poverty denotes a temporary state of deprivation, and is frequently seasonal and triggered by an individual's or household's inability to maintain income or consumption levels in times of shocks or crises (Jalan and Ravallion, 1998).

Individuals and households can fluctuate between different degrees of poverty and shift in and out of deprivation, vulnerability, and wellbeing (Leach *et al*., 1999; Little *et al*., 2008; Sallu *et al*., 2010). Poor people often find themselves in poverty traps – situations in which escaping poverty becomes impossible without external assistance due to unproductive or inflexible asset portfolios (Barrett and McPeak, 2006). A poverty trap can also be seen as a "critical minimum asset threshold, below which families are unable to successfully educate their children, build up their productive assets, and move ahead economically over time" (Carter *et al*., 2007 p.837). As of 2008, a total of 320 to 443 million of people were trapped in chronic poverty (Chronic Poverty Research Centre, 2008), leading Sachs (2006) to label <$1.25/day poverty as a trap in itself. Poverty traps at the national level are often related to poor governance, reduced foreign investment, and conflict (see Chapter 10).

13.1.3. Inequality and Marginalization

Specific livelihoods and poverty alone do not necessarily make people vulnerable to weather events and climate. The socially and economically disadvantaged and the marginalized are disproportionately affected by the impacts of climate change and extreme events (*robust evidence*) (Kates, 2000; Paavola and Adger, 2006; Adger *et al*., 2007; Cordona *et al*., 2012). These include the poor and indigenous people in North America (Field *et al*., 2007) and Africa (Boko *et al*., 2007). Inequality is a useful lens for examining why multidimensional poverty continues to exist, and in some cases has increased, despite poverty reduction efforts. Vulnerability, or the propensity or predisposition to be adversely affected (Field *et al*., 2012a) by climatic risks and other stressors, emerges from the intersection of different inequalities, and uneven power structures, and hence is socially-differentiated (Sen, 1999; Banik, 2009; Field *et al*., 2012a). Vulnerability is often high among indigenous people, women, children, the

elderly, and disabled people due to multiple deprivations that inhibit the poor and marginalized from managing daily risks and shocks (Eriksen and O'Brien, 2007; Ayers and Huq, 2009; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; O'Brien *et al*., 2010; Petheram *et al*., 2010; OECD, 2011), and may present significant barriers to adaptation.

Global inequality is persistent. In 2007, the top quintile of the world's population received 83% of total the income whereas the bottom quintile took in 1% (Ortiz and Cummins, 2011). Within most countries, income inequality has increased as economic activity and sector-specific growth constrains the productive capacity of the poor who disproportionately bear the externalities of economic growth such as environmental degradation (UNRISD, 2010; UNDP, 2011b). An inequality lens also highlights growing poverty in MICs and HICs (Gower *et al*., 2012; Gough, 2012; Taylor and Xiaoyun, 2012; Sumner, 2012b). Recognizing how inequality and marginalization perpetuate multidimensional poverty is an essential prerequisite for climate-resilient development pathways (see 13.4).

13.1.4. Interactions between Livelihoods, Poverty, Inequality, and Climate Change

This chapter opens its analytical lens from a conventional focus on poor developing countries as the prime victims of climate change to a broader understanding of livelihood and poverty dynamics and inequalities across spatial and temporal scales, revealing the highly unequal impacts of climate change. It highlights the bidirectional relationship between climate change and poverty. Addressing structural inequalities that create and sustain poverty and vulnerability (Huq *et al*., 2005; Schipper, 2007; Lemos *et al*., 2007; Boyd and Juhola, 2009; Williams, 2010; Perch, 2011) is "a prerequisite for sustainability in the context of climate change" (Field *et al*., 2012a, p.20). Uneven social relations that disproportionally burden the poorest with the brunt of climate change's negative impacts, if ignored, contribute to maladaptation (Barnett and O'Neill, 2010).

Poverty and persistent inequality are the "most salient of the conditions that shape climate-related vulnerability" (Ribot, 2010, p.50), affect livelihood options and trajectories, and create conditions in which people have few assets to liquidate in times of hardship or crisis (Mearns and Norton, 2010). The poor and marginalized usually have the least buffer to face even modest climate hazards and suffer most from successive events with little time for recovery. They are the first to experience asset erosion, poverty traps, and barriers and limits to adaptation. As shown in sections 13.2 and 13.3, climate change is an additional burden to the poor (*very high confidence*), and it will force some poor from transient into chronic poverty and create new poor (*high confidence*).

The complex interactions among weather events and climate, dynamic livelihoods, multidimensional poverty and deprivation, and persistent inequalities create an ever-shifting context of risk. Climate change, climate variability, and extreme events synergistically add on to and often reinforce other environmental, social, and political calamities (Field *et al*., 2012a). Despite the recognition of these complex interactions, the literature shows no single conceptual framework that captures them concurrently, and few studies exist that overlay gradual climatic shifts or rapid-onset events onto livelihood risk spaces. Hence, explicit attention to how livelihood dynamics interact with climatic and non-climatic stressors is useful for identifying processes that force poor and vulnerable people onto undesirable trajectories and trap them in destitution, constitute critical thresholds beyond which a certain livelihood is no longer feasible, or offer escape routes toward enhanced wellbeing. Figure 13-2 illustrates these dynamics.

[INSERT FIGURE 13-2 HERE
Figure 13-2: Livelihood dynamics under simultaneous climatic, environmental, and socioeconomic stressors and shocks leading to differential risk spaces and livelihood trajectories over a lifetime.]

13.2. Assessment of Climate Change Impacts on Livelihoods and Poverty

This section reviews the evidence and agreement about the relationships among climate change, livelihoods, poverty, and inequality. It first describes observed impacts to date (13.2.1) and then projected impacts (13.2.2). The focus on climate change effects on livelihood decision making and trajectories, spatial distributions of poverty and shifts from transient to chronic poverty, and differential vulnerability and poverty traps due to intersecting inequalities demonstrates the multifaceted interactions between weather events and climate and non-climatic

stressors. Building on deductive reasoning and theorized linkages among climate change, livelihoods, and poverty, this section draws on a wide range of empirical studies and simulations to provide evidence across multiple scales, contexts, and social and environmental processes to assess climate change impacts. Cases of observed impacts often rely on qualitative data, and sometimes lack methodological clarity and rigorous detection and attribution.

13.2.1. Evidence of Observed Climate Change Impacts on Livelihoods and Poverty

Weather events and climate impact the lives and livelihoods of millions of poor people (Field *et al.*, 2012b). Even minor changes in precipitation amount or temporal distribution, short periods of extreme temperatures, or localized weather events can have serious impacts on livelihoods (Douglas *et al.*, 2008; Ostfeld, 2009; Midgley and Thuiller, 2011). Many such events remain unrecognized given that standard climate observations typically report precipitation or temperature by month, season, or year, thus obscuring changes that directly impact decision making, for instance, in agriculture (Tennant and Hewitson, 2002; Barron *et al.*, 2003; Usman and Reason, 2004; Douglas *et al.*, 2008; Salack *et al.*, 2012; Lacombe *et al.*, 2012). This difficulty in detection and attribution is compounded by a lack of long-term continuous and dense networks of climate data in many LICs (UNECA, 2011) and, as shown for the Sumbanese in Eastern Indonesia, by phenomenological experiences of events such as drought (Orr *et al.*, 2012).

13.2.1.1. Impacts on Livelihood Assets and Human Capabilities

Climate change, climate variability and extreme events interact with numerous aspects of people's livelihoods. This section presents empirical evidence of impacts on natural, physical, financial, human, and social and cultural assets.

Weather events and climate impact *natural assets* on which certain livelihoods depend, such as rivers, lakes, and fish stocks (*robust evidence*) (Thomas *et al.*, 2007; Nelson and Stathers, 2009; Osbahr *et al.*, 2010; Bunce *et al.*, 2010a; Bunce *et al.*, 2010b; D'Agostino and Sovacool, 2011) (see Chapters 3, 4, 5, 6, and 30). During the 20th century, water temperatures increased in Lake Tanganyika and winds decreased (Verburg and Hecky, 2009; Adrian *et al.*, 2009; Tierney *et al.*, 2010). Thus, studies since the late 1970s have observed a 20% drop in primary production and a 30% decline in fish, a key protein source in the area; these drops may exceed effects of overfishing and other human impacts (O'Reilly *et al.*, 2003). The Middle East and North Africa (MENA) face dwindling water resources due to less precipitation and rising temperatures combined with mounting water demand due to population and economic growth (Tekken and Kropp, 2012), resulting in rapidly decreasing water availability, expected to be 30-70% less per person in 2025 (Sowers *et al.*, 2011). In MENA (Sowers *et al.*, 2011), the Andes and Himalayas (Orlove, 2009), the Caribbean (Cashman *et al.*, 2010), Australia (Alston, 2011), and in cities (Satterthwaite, 2011), policy allocation often favors more affluent consumers, at the expense of less powerful rural and/or poor users.

Weather events and climate also erode farming livelihoods (see Chapters 7, 9), via declining crop yields (Hassan and Nhemachena, 2008; Apata *et al.*, 2009; Sissoko *et al.*, 2011; Sietz *et al.*, 2012), at times compounded by increased pathogens, insect attacks, and parasitic weeds (Stringer *et al.*, 2007; Byg and Salick, 2009), and reduced availability of and access to non-timber forest products (Hertel and Rosch, 2010; Nkem *et al.*, 2012), and biodiversity and medicinal plants (Van Noordwijk, 2010). For agropastoral and mixed crop-livestock livelihoods, extreme high temperatures threaten cattle (Hahn, 1997; Thornton *et al.*, 2007; Mader, 2012; Nesamvuni *et al.*, 2012) ; in Kenya, for instance, people may shift from dairy to beef cattle and from sheep to goats (Kabubo-Mariara, 2008).

The most extreme form of erosion of natural assets is the complete disappearance of people's land on islands and in coastal regions (McGranahan *et al.*, 2007; Solomon *et al.*, 2009; Perch and Roy, 2010) (see Chapter 5). Densely populated coastal cities with high poverty counts such as Alexandria and Port Said in Egypt (El-Raey *et al.*, 1999), Cotonou in Benin (Dossou and Glehouenou-Dossou, 2007), and Lagos and Port Harcourt in Nigeria (Abam *et al.*, 2000; Fashae and Onafeso, 2011) have already been affected by floods and are at risk of submersion, while resettlements are planned for the Mekong River Delta and the Limpopo River (de Sherbinin *et al.*, 2011).

Damage to *physical assets* due to weather events and climate is well documented for poor urban settlements, often built in risk-prone floodplains and hillsides susceptible to erosion and landslides. Impacts include homes destroyed

by flooding water and disrupted water and sanitation services. Flooding has adversely affected large African cities (e.g., Accra, Nairobi, Kampala, and Lagos), mainly due to inadequate drainage and increasing precipitation in dense settlements (Douglas *et al*., 2008), and informal settlements in Latin American cities (Hardoy and Pandiella, 2009; Hardoy *et al*., 2011). Loss of physical assets in poor areas after disasters is often followed by looting (Hardoy and Pandiella, 2009) and displacement due to loss of property (Douglas *et al*., 2008). Increasing flash floods attributed to climate change (Sudmeier-Rieux *et al*., 2012) have severely damaged physical assets in the Himalayas, such as terraces, orchards, stream embankments, and roads (Hewitt and Mehta, 2012; Azhar-Hewitt and Hewitt, 2012).

Erosion of *financial assets* during periods of increased climate stress result from loss of farm income and jobs (Hassan and Nhemachena, 2008; Iwasaki *et al*., 2009; Alderman, 2010; Jabeen *et al*., 2010; Alston, 2011) and increased costs of living (Gabrielsson *et al*., 2012). Urban flooding in Lagos slums undermines job opportunities (Adelekan, 2010). Income losses due to weather events are compounded by expenses for agricultural inputs (seeds, equipment), school tuition, uniforms, and books, and health expenses throughout the year (Thomas *et al*., 2007).

Equally important, albeit frequently overlooked, is the damage to *human assets* as a result of weather events and climate, such as increased food insecurity, undernourishment, and chronic hunger due to failed crops (*medium evidence*) (Misselhorn, 2005; Patz *et al*., 2005; Funk *et al*., 2008; Gentle and Maraseni, 2012) or spikes in food prices most severely felt among poor urban populations (Ahmed *et al*., 2009; Hertel and Rosch, 2010). During the Ethiopian drought (1998-2000) and Hurricane Mitch in Nicaragua (1998), poorer households tended to engage in asset smoothing, reducing their consumption to very low levels to protect their assets, whereas wealthier households sold assets and smoothed consumption (Carter *et al*., 2007). In such cases, the poor further erode nutritional levels and human health while desperately holding on to their limited assets. Dehydration, heat stroke, and heat exhaustion, from exposure to heat waves undermine people's ability to carry out physical work outdoors and indoors (Semenza *et al*., 1999; Kakota *et al*., 2011) (see Chapter 11). Psychological effects from extreme events include sleeplessness, anxiety and depression (Byg and Salick, 2009; Keshavarz *et al*., 2013), loss of sense of place and belonging (Tschakert *et al*., 2011; Willox *et al*., 2012), and suicide (Caldwell *et al*., 2004; Alston, 2011) (*medium evidence*).

Finally, weather events and climate also erode *social and cultural assets*. A series of climatic and non-climatic stressors and changing trends disrupt informal social networks of the poorest, elderly, women, and women-headed households, preventing mobilization of labor and reciprocal gifts (Osbahr *et al*., 2008; Buechler, 2009), as well as formal social networks, including social assistance programs (Douglas *et al*., 2008). Indigenous people (see Chapter 12) witness their cultural points of reference disappearing (Ford, 2009; Green *et al*., 2010; Bell *et al*., 2010).

13.2.1.2. Impacts on Livelihood Dynamics and Trajectories

Weather events and climate also affect livelihood trajectories and dynamics in livelihood decision making, often in conjunction with cross-scalar socio-economic, institutional, or political stressors. Shifting in and out of hardship, vulnerability, and wellbeing on a seasonal basis is not uncommon. To a large extent, these shifts from coping and hardship to recovery are driven by annual and inter-annual climate variability. Figure 13-3 illustrates an annual "wheel of hardship" for the Lake Victoria Basin in East Africa (Gabrielsson *et al*., 2012).

[INSERT FIGURE 13-3 HERE
Figure 13-3: 'Wheel of hardship' – a generalized seasonal calendar depicting livelihood conditions and stress based on experiences of smallholder farmers in the Lake Victoria Basin in Kenya and Tanzania (Gabrielsson *et al*., 2012).]

Shifts in livelihoods often occur due to changing climate trends, linked to a series of environmental, climatic, and political stressors (*robust evidence*). Farmers may change their crop choices instead of abandoning farming (Kurukulasuriya and Mendelsohn, 2007) or take on more lucrative income-generating activities (see Figure 13-2). Around Mali's drying Lake Faguibine, livelihoods shifted from water-based to agro-sylvo-pastoral systems, as a direct impact of lower rainfall and more frequent and more severe droughts (Brockhaus and Djoudi, 2008). Diverse indigenous groups in Russia have changed their livelihoods as result of Soviet legacy and climate change; for example, many Viliui Sakha have abandoned cow-keeping due to youth out-migration, growing access to consumer goods, and seasonal changes in temperature, rainfall, and snow (Crate, 2013). Under certain converging shocks and

stressors, people adopt entirely new livelihoods. After Hurricane Stan (2005), land-poor coffee farmers in Chiapas, Mexico, turned from specializing in coffee to being day laborers and subsistence farmers (Eakin *et al.*, 2012). In South Africa, higher precipitation uncertainty raised reliance on livestock and poultry rather than crops alone in 80% of households interviewed (Thomas *et al.*, 2007). In South India and southern Africa people migrated to the coasts, switching from climate-sensitive farming to marine livelihoods (Coulthard, 2008; Bunce *et al.*, 2010a; Bunce *et al.*, 2010b). In West Africa, shifting seasonality of rains hamper crop and water management of small-scale farmers (Yengoh *et al.*, 2010a; Yengoh *et al.*, 2010b; Armah *et al.*, 2011; Karambiri *et al.*, 2011; Lacombe *et al.*, 2012).

13.2.1.3. Impacts on Poverty Dynamics: Transient and Chronic Poverty

Limited evidence documents the extent to which climate change intersects with poverty dynamics, yet, there is *high agreement* that shifts from transient to chronic poverty due to weather and climate are occurring, especially after a series of weather or extreme events (Scott-Joseph, 2010). Households in transient poverty may become chronically poor due to a lack of effective response options to weather events and climate, compared with more affluent households (see Figure 13-2). Often, multiple deprivations drive these shifts, with socially and economically marginalized groups particularly prone to slipping into chronic poverty. Limited and maladaptive responses such as sending younger children to work may contribute (Tanner and Mitchell, 2008). Women-headed households, people in informal settlements, children, and indigenous communities are particularly at risk, due to compounding stressors such as lack of governmental support, urban infrastructure, and formal land tenure (see 13.2.1.5 and Chapter 12).

Urban poor in Africa, Asia, and Latin America may slip from transient to chronic poverty given the combination of population growth and flooding threats in low-elevation cities and growth and water stress in drylands (Balk *et al.*, 2009), along with other multiple deprivations (Mitlin and Satterthwaite, 2013). Poverty shifts also occur in response to food price increases, though the strength of the relationship between weather events and climate and food prices is still debated (see Chapter 7 and 13.3.1.4). Urban poor are particularly at risk since they are almost exclusively net buyers of food (Cranfield *et al.*, 2007; Cudjoe *et al.*, 2010; Ruel *et al.*, 2010). In rural areas, those dependent on natural resources may also slip from transient to chronic poverty, for instance when access to forests is restricted, e.g., under conservation efforts or conflicts, and alternative income-generating resources such as non-timber forest products become unavailable, particularly for women-headed households (Shackleton *et al.*, 2007; Fisher *et al.*, 2010). In southern Africa, Misselhorn (2005) showed in a meta-study of 49 cases of food insecurity that climatic drivers and poverty were the two dominant and interacting causal factors. Poor pastoralists have collapsed into chronic poverty when livestock assets have been lost (Thornton *et al.*, 2007). Many of these shifts remain undetected, incompletely captured in poverty data and adaptation monitoring. The bulk of attention is oriented toward extreme events, rapid-onset disasters, and subsequent impacts on livelihoods and the poor. Subtle changes are rarely tracked, making quantification of long-term trends and attribution difficult.

13.2.1.4. Poverty Traps and Critical Thresholds

Poverty traps arise when climate change, variability, and extreme events make the poor even poorer. Yet, attribution remains a challenge. Among the urban poor, poverty traps have been reported especially for wage laborers who erode their financial capital due to increases in food prices (Ahmed *et al.*, 2009; Hertel and Rosch, 2010) and for those in informal settlements exposed to floods and landslides, with nowhere else to go and no governmental support (Hardoy and Pandiella, 2009). In rural areas, poverty traps are reported when poverty impacts of climate change persist over decades, mainly due to recurring stress on ecological systems and environmental degradation, such as in the Sahel (Kates, 2000; Hertel and Rosch, 2010; Sissoko *et al.*, 2011; UNCCD, 2011), and when people are unable to rebuild assets after a series of stresses (Eriksen and O'Brien, 2007; Sabates-Wheeler *et al.*, 2008; Sallu *et al.*, 2010). Poverty traps and destitution are also described in pastoralist systems, triggered through droughts, restricted mobility due to conflict and insecurity, adverse terms of trade, and the conversion of grazing areas to agricultural land, such as for biofuel production (Eriksen and Lind, 2009; Homewood, 2009; Eriksen and Marin, 2011). Other poverty traps result from heavy debt loads due to the inability to repay loans and distress sales (Renton, 2009; Ahmed *et al.*, 2012) and persistent discrimination through legal structures and formal institutions, especially for women and other marginalized groups (Campbell *et al.*, 2009; McDowell and Hess, 2012). Culturally-induced

poverty traps also exist, such as forced kin solidarity in farming systems in Ethiopia, due to which more affluent farmers avoid investing in soil fertility, which would protect against climate shocks (Di Falco and Bulte, 2012).

Despite *limited evidence*, there is *high agreement* that critical thresholds, or irreversible damage (Heltberg *et al*., 2009), result from the convergence of various factors, many of which are not directly related to climate change. For instance, the poor often rely on social networks, including reciprocal gifts and exchanges, to protect themselves from shocks and crises such as droughts (Little *et al*., 2006). Yet, given limited assets and ability to mobilize labor and food, particularly for smaller and women-headed households and the elderly, the exhaustion of these reciprocal ties can indicate an imminent slipping into poverty traps or chronic poverty (Pradhan *et al*., 2007; Osbahr *et al*., 2008). Injuries, disabilities, disease, psychological distress, for instance from accidents following flood events, critically lower poor people's main asset, labor (Douglas *et al*., 2008), and may plunge poor individuals and households deeper into deprivation, forcing some over critical thresholds into chronic poverty.

Few studies illustrate positive livelihood trajectories as a result of climate change or climate-induced shocks, and they tend to refer to more affluent and powerful constituencies while very scarce evidence exists of poor people escaping poverty traps (see Box 13-1). In Honduras, for example, Hurricane Mitch (1998) helped the poor to bring about institutional changes, more equitable land distribution, and better flood preparedness (McSweeney and Coomes, 2011). In Lake Victoria Basin, collective actions have emerged as a result of HIV/AIDS and climate change, enhancing social asset accumulation (Gabrielsson and Ramasar, 2012).

13.2.1.5. Implications for Inequality

Climate variability and change as well as climate-related disasters contribute to and exacerbate inequality, both in urban and in rural areas, in LICs, MICs, and HICs. Mounting inequality is not just a side effect of weather and climate but of the interaction of related impacts with multiple deprivations at the context-specific intersections of gender, race, class, caste, indigeneity, age, and (dis)ability, embedded in uneven power structures, also known as intersectionality (Shields, 2008; Nightingale, 2011). In many cities in Latin America, upper middle- and high-income people living in flood-prone areas or high-risk slopes can afford insurance and lobby for protective policies, in contrast to poor residents (Hardoy and Pandiella, 2009). In northern welfare states, in the aftermath of the financial crisis, modified social policies and fiscal regimes amplify unevenly distributed climate impacts (Gough, 2012). This section illustrates how climate impacts intersect with inequality, primarily along the lines of gender, age, and indigeneity, cross-referencing other dimensions of inequality covered in other chapters.

_____ START BOX 13-1 HERE _____

Box 13-1. Climate and Gender Inequality: Complex and Intersecting Power Relations

Preexisting ***gender inequality*** is increased or highlighted as a result of weather events and climate-related disasters intertwined with socioeconomic, institutional, cultural, and political drivers that perpetuate differential vulnerabilities (*robust evidence*) (Lambrou and Paina, 2006; Brouwer *et al*., 2007; Shackleton *et al*., 2007; Adger *et al*., 2007; Carr, 2008; Demetriades and Esplen, 2008; Galaz *et al*., 2008; Osbahr *et al*., 2008; Buechler, 2009; Hardoy and Pandiella, 2009; Nightingale, 2009; Renton, 2009; Terry, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resurreccion, 2011; Zotti *et al*., 2012). While earlier studies have tended to highlight women's quasi-universal vulnerability in the context of climate change (e.g. Denton, 2002), this general thrust can mask the complex and intersecting power relations and other deep structural and place-based causes of inequality (Nightingale, 2009; UNFPA, 2009; Arora-Jonsson, 2011). Moreover, the construction of economically poor women as vulnerable victims is a one-dimensional narrative that denies women's agency and emphasizes their vulnerability as their intrinsic problem (MacGregor, 2010; Manzo, 2010; Arora-Jonsson, 2011).

Gendered livelihood impacts: Men and women are affected by climate variability and change, albeit differentially. Campbell *et al*. (2009) and Resurreccion (2011), in case studies from Vietnam, found increased workloads for both partners linked to weather events and climate, contingent on socially accepted gender roles: men tend to work longer hours during extreme events and women take on extra responsibilities during disaster preparation and recovery (e.g.,

storing food and water and taking care of the children, the elderly, and the sick) and when their husbands migrate. In Cambodia, Khmer men and women accepted culturally-taboo income-generating activities under duress, when rice cropping patterns shifted due to increased temperatures and more irregular rainfall (Resurreccion, 2011). The ten-year drought in Australia's Murray-Darling Basin differentially affected men and women, due to their distinct roles within agriculture (e.g. Eriksen *et al*., 2010). Alston (2011) noted social disruption and depression, most profound in areas with almost total reliance on agriculture, no substitute employment, and limited service infrastructure (Table 13-1). Climate variability amplifies food shortages in which women consume less food and suffer from water-borne diseases and reproductive tract infections following floods (Neelormi *et al*., 2008; Campbell *et al*., 2009). In Nepal, shifts in the monsoon season, longer dry periods, and decreased snowfall force Dalit girls and women ('untouchable' caste) to grow drought-resistant buckwheat and provide more day labor to the high caste Lama landlords while Dalit men seek culturally-taboo patronage protection to engage in cross-border trade (Onta and Resurreccion, 2011).

Feminization of responsibilities: Increased workloads due to weather events and climate are often unevenly distributed, adding to already long lists of women's labor and caring duties (Nelson and Stathers, 2009; MacGregor, 2010; Petrie, 2010; Arora-Jonsson, 2011; Kakota *et al*., 2011; Resurreccion, 2011). The additional work for women, as shown in South Africa, takes a psychological and physical toll (Babugura, 2010). In Ghana, some husbands prevent their wives from engaging in additional agricultural production as a response to gradually shifting rainfall seasonality, thereby undermining both women's agency as well as overall household wellbeing (Carr, 2008).

Occupational hazards: Increasing cases of heat death are reported among male workers on sugarcane plantations in El Salvador due to kidney failure (Peraza *et al*., 2012) and heat-related indoor work emergencies in Spain among young (<50) able-bodied urban men (García-Pina *et al*., 2008) while anecdotal evidence suggests that women tea pickers in Malawi, Kenya, India, and Sri Lanka suffer and die from heat stress as payment by quantity undermines rest breaks (Renton, 2009) (see Chapter 11). In cases of male outmigration due to unsustainable rural livelihoods, women in Bangladesh face unsafe working conditions, exploitation, and loss of respect (Pouliotte *et al*., 2009).

Emotional and psychological distress: Climate-related disasters or gradual environmental deterioration can affect women's mental health disproportionally due to their multiple social roles (UN ECLAC, 2005; Demetriades and Esplen, 2008; Babugura, 2010; Hargreaves, 2013). Increased gender-based violence within households is reported as a social consequence of weather events and climate, including incremental climate change, not just disasters, due to greater stress, family conflict, and disrupted safety nets, in Australia (Alston, 2011; Parkinson *et al*., 2011; Whittenbury, 2013), the U.S. (Jenkins and Phillips, 2008; Anastario *et al*., 2009), and LICs such as Vietnam (Campbell *et al*., 2009) and Bangladesh (Pouliotte *et al*., 2009). In Nepal, human trafficking of girls and women may have increased by 20-30% during political conflict and floods and droughts (Nellemann *et al*., 2011).

Mortality: During floods, social conditioning often constrains poor women's mobility as many are not allowed to learn how to swim (Demetriades and Esplen, 2008); yet, in Nicaragua, it forced middle-class women to stay in risk-prone houses (Bradshaw, 2010). More women die in hurricanes and floods when they are socio-economically disadvantaged and the disasters exacerbate existing patterns of discrimination (Neumayer and Plümper, 2007; Ray-Bennett, 2009). Evidence from Hurricane Mitch and other disasters shows a higher mortality rate among men in the case of culturally-imposed roles as heroic life-savers (Röhr, 2006; Campbell *et al*., 2009; Resurreccion, 2011).

[INSERT FIGURE 13-4 HERE
Figure 13-4: Intersecting dimensions of inequality.]

[INSERT TABLE 13-1 HERE
Table 13-1: Gendered impacts of Australia's ten-year drought.]

_____ END BOX 13-1 HERE _____

Medium evidence highlights impacts of climate stresses and extreme events on *children* (Cutter *et al*., 2012; O'Brien *et al*., 2012). Children in urban slums suffer from inadequate water supplies and malnutrition, which exacerbates impacts from heat stress, while excessive rain heightens water-borne diseases (Bartlett, 2008). Flood-related mortality in Nepal was twice as high for girls as for women (1.33% versus 0.6%) and also higher for boys than for

men, and for young children in general six times higher than before the flood (Pradhan *et al.*, 2007). Lower caloric intake due to two back-to-back droughts and price shocks in Zimbabwe in the 1980s has resulted in physical stunting among children and reduced lifetime earnings (Alderman, 2010). In Mali, the incidence of child food poverty increased from 41% to 52% since the 2006 food price increases (Bibi *et al.*, 2010).

Health impacts of weather events and climate differentially affect *the elderly* and *socially isolated* (Frumkin *et al.*, 2008). In Vietnam the elderly, widows, and disabled people, in addition to single mothers and women-headed households with small children, were least resilient to floods and storms and slow-onset events such as recurrent drought (Campbell *et al.*, 2009). In Australia, older citizens have shown feelings of distress as a result of familiar landscapes altered by drought, loss of home gardens, social isolation, and physical harm related to heat stress and wild fires (Pereira and Pereira, 2008; Horton *et al.*, 2010; Polain *et al.*, 2011). Elderly citizens in the U.K. may experience higher vulnerability to heat waves due to misinformation propagated through bonding networks (Wolf *et al.*, 2010). Studies in Europe, U.S., U.K., Japan, Korea, and New Zealand report higher heat-related mortality among the elderly, children, and persons of lower socio-economic status (Baccini *et al.*, 2008). Much evidence, though anecdotal, suggests differential damages of Hurricane Sandy in New York (2012).

Inequality and disproportionate effects of climate-related impacts also occur along the axes of *indigeneity* and *race*. Examples include low-income African-American residents of New Orleans after Hurricane Katrina (Elliott and Pais, 2006), Afro-Latinos and displaced indigenous groups in urban Latin America (Hardoy and Pandiella, 2009), and the indigenous in the Russian North (Crate, 2013) and Bolivia's highlands (Andersen and Verner, 2009; Valdivia *et al.*, 2010; McDowell and Hess, 2012). See Chapter 12 for diverse impacts on indigenous cultures and lifestyles.

13.2.2. Understanding Future Impacts of Climate Change on Livelihoods and Poverty

Future climate change, as projected through modeling, will continue to affect poor people in rural and urban areas, both in the global North and South, alter their livelihoods, and make efforts to reduce poverty more difficult (*high confidence*). Studies reveal a broad range of future impacts, depending on the climatic, agro-economic, and demographic models employed, their key variables, time frame, ranging from 2016-2100, and spatial scale, varying from a country's agro-ecological zones to the global. Only some projections include adaptation.

Projections emphasize the complexity and heterogeneity of future climate impacts, including winners and losers in close geographic proximity. Anticipated impacts are expected to interact with multiple stressors, most notably social vulnerability (Iglesias *et al.*, 2011), low adaptive capacity and subsistence constraints under extreme poverty (Liu *et al.*, 2008), natural resource dependence (Adano *et al.*, 2012), population increases (Müller *et al.*, 2011), weak institutional support (Menon, 2009; Xu *et al.*, 2009; Skoufias *et al.*, 2011a; Skoufias *et al.*, 2011b), ethnic conflict and political instability (Challinor *et al.*, 2007; Adano *et al.*, 2012), large-scale land conversions (Assuncao and Cheres, 2008; Thornton *et al.*, 2008), and inequitable trade relations (Challinor *et al.*, 2007; Jacoby *et al.*, 2011).

13.2.2.1. Projected Impacts by Geographic Region

Climate change will exacerbate vulnerability and in turn further entrench poverty (*very high confidence*). Wheeler (2011) employs an extensive dataset to analyze climate risk and coping ability by country. The 20 countries most at risk of extreme weather in 2015 will include those with considerable poverty, although not all poor people will be at risk. Of these top 20, seven are LICs (Bangladesh, Ethiopia, Kenya, Madagascar, Mozambique, Somalia, and Zimbabwe), eight are lower MICs (Bolivia, Djibouti, Honduras, India, Philippines, Sri Lanka, Vietnam, and Zambia), four are upper MICs (China, Colombia, Cuba, and Thailand), and one is a HIC (Hong Kong). For the top five (China, Djibouti, India, Kenya, and Somalia), climate contributes between 46.4% and 87.5% to a 2008-2015 increase in national vulnerability, in contrast to income, urbanization, and regulation. Highest vulnerability to sea level rise by 2050, based on low-elevation coastal zones, areas of storm surge zones, and population density, is expected for India, China, Indonesia, and the Philippines (all MICs) and Bangladesh (LIC), while Qatar, Bahamas, and Bahrain (all HICs) show the highest percentage of vulnerable population (>30%). India and Indonesia are projected to experience a 80% and 60% increase, respectively, in the sizes of their populations vulnerable to sea

level rise, housing a combined total of over 58 million of the most vulnerable people by 2050; an increase of six million people vulnerable to sea level rise in China will bring its total to 22 million, and Bangladesh's vulnerable population is predicted to grow to 27 million people – more than double its 2008 size (Wheeler, 2011).

Geographically, highly vulnerable regions are those exposed to sea-level rise and extreme events overlaid with high concentrations of multidimensional poverty, including pockets of poor people in MICs: mega-deltas in Bangladesh, Thailand, Myanmar, and Vietnam (Eastham *et al.*, 2008; Wassmann *et al.*, 2009), watersheds in the Himalayas (Xu *et al.*, 2009), ecologically-fragile areas in China (Taylor and Xiaoyun, 2012), drylands (Anderson *et al.*, 2009; Piao *et al.*, 2010), mountain areas (Beniston, 2003; Valdivia *et al.*, 2010; Gerlitz *et al.*, 2012; McDowell and Hess, 2012; Gentle and Maraseni, 2012), river deltas subject to resource extraction (Syvitski *et al.*, 2009), and coastal areas with severe ecosystem deterioration in eastern and southern Africa (Bunce *et al.*, 2010a; Bunce *et al.*, 2010b).

13.2.2.2. Anticipated Impacts on Economic Growth and Agricultural Productivity

The majority of projected impact studies focus on the anticipated consequences of climatic changes and shocks on agricultural productivity, mainly in Africa, Asia, and Latin America and primarily focus on impacts on economic growth, changes in food prices and food security, and, subsequently, extrapolated changes in poverty head counts.

For future poverty head counts impacted by climate change, the literature shows disagreement. Tubiello et al. (2008) project that, by 2080, the number of undernourished people could increase by up to 170 million, using the A2 SRES scenarios, and up to a total of 1,300 million people assuming no CO_2 fertilization. In contrast, Skoufias et al. (2011b), using 2055 predictions based on the Nordhaus (2010) ICE model, state that under business as usual and optimal abatement, poverty (measured at $2/day) could be reduced by 800 million people, due to annual, global, and real per capita growth rate of 2.2% up to 2055. However, lower probability extreme events would reverse this trend, and mitigation under optimal abatement typically excludes the poor (Skoufias *et al.*, 2011b). One study of Zambia illustrates the range of potential shifts in poverty headcounts based on climate change and responses. Thurlow et al. (2009) estimate that by 2016, Zambia's poverty headcount would increase by 300,000 people under average climate variability, and by 650,000 under a worst ten-year rainfall sequence.

Projections of future climate change impacts on GDP use non-disaggregated poverty data. For instance, Mendelsohn et al. (2006) use dynamic coupled ocean–atmosphere models and market response functions to simulate the distribution of climate impacts for 2100. Independent of the climate scenarios, poor countries, mainly in Africa and Southeast Asia, will face the largest losses (0.2-1.2% reduction in GDP) and, under experimental models, up to 23.8% drop in GDP; in contrast, the richest quartile will encounter both positive and negative effects, ranging -0.1% to +0.2% GDP, and up to a 0.9% GDP increase under experimental models. Changes in GDP reflect climate-sensitive economic sectors, especially water and energy, with poor nations in low latitudes already facing high temperatures and thus more vulnerable to decreased agricultural productivity with increased warming.

A growing body of literature estimates future changes in agricultural production and food prices due to climate change, variability, and extreme events, primarily in the global South (Slater *et al.*, 2007; Thomas *et al.*, 2007; Assuncao and Cheres, 2008; Burke *et al.*, 2011). Mixed trends are projected for major staples for all continents until the mid of the 21st century (see Chapter 7). By mid-century the production of coarse grains in Africa may be reduced by 17-22 % due to climate change; the well-fertilized modern seed varieties seem more susceptible to heat stress than traditional ones (Schlenker and Lobell, 2010). By 2080, a significant decrease in land productivity is expected for sub-Saharan Africa (-14% to -27%) and Southeast Asia (-18% to -32%), coupled with increase in water demand, while lowest risks are projected for North America, Europe, East Asia, Russia, and Australia (Iglesias *et al.*, 2011).

13.2.2.3. Implications for Livelihood Assets, Trajectories, and Poverty Dynamics

Projections of future climate change impacts on livelihood assets highlight the erosion of financial capital as a result of increased food prices (Thurlow *et al.*, 2009; Seo *et al.*, 2009; Ahmed *et al.*, 2009; Hertel *et al.*, 2010; Jacoby *et al.*, 2011; Skoufias *et al.*, 2011b), human assets due to decline in nutritional status (Liu *et al.*, 2008), and natural

assets due to lower agricultural productivity (Thurlow *et al*., 2009; Jones and Thornton, 2009; Skoufias *et al*., 2011b). They also show a substantial increase in future heat-related mortality (Basu and Samet, 2002; McGregor *et al*., 2006; Sherwood and Huber, 2010; Huang *et al*., 2011), increasing infectious disease transmission rates (Green *et al*., 2010), and other health impacts (see Chapter 11). Impacts on social and cultural assets have received little attention. Exceptions address losses of social identity and cultural connections with land and sea among indigenous populations threatened by sea level rise and potential relocation (Green *et al*., 2010) and conflicts between ethnic and/or religious groups (Adano *et al*., 2012) (see Chapter 12). Poor households with limited social networks will be worst off, including in places such as Nepal (Menon, 2009) and Indonesia (Skoufias *et al*., 2011a).

Climate change is also projected to cause shifts in livelihood trajectories. Simulated probabilities of failed seasons, using current daily rainfall data and 2050 projections in the length of growing period, show transitions from cropping to livestock in marginal cropping areas in Africa (Thomas *et al*., 2007; Jones and Thornton, 2009). By 2050, expanding vector populations, especially tsetse, and a >20% reduction in the length of the growing period, as simulated under HadCM3 and A1F1, are expected for livestock-dependent livelihoods and mixed crop-livestock livelihoods in semi-arid to arid Africa and Asia, combined with increasing water scarcity and loss in stovers due to maize substitution (Thornton *et al*., 2007), which will stress livelihoods of poor farmers and pastoralists.

Future climate change impacts on disaggregated poverty are mainly addressed through projected changes in food prices and price-induced earnings associated with impacts on agricultural production (Schmidhuber and Tubiello, 2007). Changes in price-induced earnings lower the welfare of low-income households, particularly urban and wage-labor dependent households that use a large income share to purchase staple crops. For instance, a one-time maximum extreme dry event, simulated for 1971-2000 and 2071-2100 using the IPCC-SRES A2 scenario for a sample of 16 developing countries, shows a 95-110% increase in poverty for urban wage populations in Malawi, Zambia, and Mexico, while self-employed farming households consolidate assets and face the smallest increase in vulnerability (Ahmed *et al*., 2009). Similarly, under low productivity scenarios assuming rapid temperature increase by 2030, poverty among the agricultural self-employed in 15 LICs and MICs may drop due to benefits from selling surplus production at higher prices, by as much as 40% in Chile and the Philippines; however, higher food prices may lead to a drop in national welfare, as steep as 55% in South Africa (Hertel *et al*., 2010). In most developing countries the poverty headcount is expected to decline in some occupational strata and increase in others; only in most African countries are yield impacts expected to be too severe to allow any benefits (Hertel and Rosch, 2010).

13.2.2.4. Impacts on Transient and Chronic Poverty, Poverty Traps, and Thresholds

Existing projections do not provide robust evidence to estimate whether shifts from transient to chronic poverty are expected to occur as a result of climate change, and to what extent. However, a predicted increase in the number of urban poor, especially wage laborers, suggests that a large number may shift from transient to chronic poverty due to high exposure to food price increases, or find themselves in a poverty trap, especially under scenarios with long-duration climatic shifts and prolonged droughts (Ahmed *et al*., 2009; Hertel *et al*., 2010). In Zambia, for example, almost half of the 650,000 new poor under the worst historic 10-year period projected until 2016 are expected to be in urban areas (Thurlow *et al*., 2009). In Tanzania, Ahmed et al. (2011), based on a high precipitation volatility GCM, predict up to 1.17 million new poor into the 21st century. Shifts in and out of poverty may occur by 2050 for small-scale coffee farmers in Central America, because of suitable coffee growing areas moving to higher altitudes, especially when constrained by unequal access to agro-technical and climatic information (Laderach *et al*., 2011).

Poor countries will experience greater poverty as a result of climate change and extreme events (*high confidence*), due to location and low-latitude high temperatures (Mendelsohn *et al*., 2006), anticipated further decline in adaptive capacity combined with reductions in agricultural productivity (Iglesias et al., 2011), greater inequality and deep-rooted poverty (Jones and Thornton, 2009), and lower levels of education and large numbers of young dependents (Skoufias *et al*., 2011c). Although robust projections on poverty traps are lacking, they may be associated with emerging hotspots of hunger, such as those projected for Tanzania, Mozambique, and the Democratic Republic of Congo (DRC) by 2030 (Liu *et al*., 2008). Based on SRES scenarios, Devitt and Tol (2012) simulate coupled climate change- and conflict-induced poverty traps up until 2100 for the DRC and several other sub-Saharan countries.

Some climate change projections (see WG1 Chapters 11, 12 and 14) indicate the possibility of large impacts from climate change that may exceed thresholds beyond which detrimental shocks to livelihoods and poverty may occur, unless strong adaptation and/or mitigation responses are implemented in a timely manner. In parts of Africa, particularly the Sahel, and the Indian sub-continent, the risk of heat stress may become acute toward the end of the century, preventing people from practicing agriculture (Patricola and Cook, 2010; Dunne *et al.*, 2013). Since women do most of the agricultural work, they will suffer disproportionally from heat stress; for instance, in Africa, women carry out 90% of hoeing and weeding and 60% of harvesting work (Blackden and Wodon, 2006 p. 18). In the glacier-dependent Himalayan region, excessive runoff and flooding will threaten livelihoods (Xu *et al.*, 2009). Relocation would represent a critical threshold for indigenous groups, due to sea level rise for the Torres Strait Islanders between Australia and Papua New Guinea (Green *et al.*, 2010) and permafrost degradation and increased and seasonally erratic precipitation for the Viliui Sakha in the Russian North (Crate, 2013).

13.3. Assessment of Impacts of Climate Change Responses on Livelihoods and Poverty

Climate change responses interact with social and political processes to affect sustainable development and climate resilient pathways (Chapter 20), and in turn, livelihoods and poverty. Climate mitigation and adaptation responses include formal policies by governments, NGOs, bilateral and multilateral organizations as well as actions by individuals and communities. This section reviews evidence of impacts of mitigation responses (13.3.1) and of adaptation responses (13.3.2) in the context of livelihood and poverty dynamics and inequalities. This section draws upon empirical evidence, some of which is preliminary as several policies are still in their infancy.

13.3.1. Impacts of Mitigation Responses

This section assesses the observed and potential impacts of four climate change responses on livelihoods and poverty: the two mitigation responses most significant for poverty alleviation under the UNFCCC, the CDM and REDD+, and two mitigation responses outside of the UNFCCC, voluntary carbon offsets and biofuel production. Many synergies between climate change mitigation policies and poverty alleviation have been identified in the literature (Klein *et al.*, 2005; Ürge-Vorsatz and Tirado Herrero, 2012), but evidence of positive outcomes is limited. Policies aimed at mitigating climate change are often detrimental to poor people and their livelihoods (*high confidence*) (Collier *et al.*, 2008; Böhm, 2009; Hertel and Rosch, 2010).

13.3.1.1. The Clean Development Mechanism (CDM)

The CDM (see 21.6.1.4) aims to promote social, economic, and environmental dimensions of sustainable development through progress along 15 indicators including poverty alleviation. CDM projects as diverse as low-cost energy services in India, micro-hydro projects in Bhutan and Peru, efficient firewood use in Nigeria, and biogas digesters in China, are expected to generate livelihood benefits and employment, and reduce poverty among beneficiaries, according to the UNFCCC secretariat (UNFCCC, 2011; UNFCCC, 2013). However, most of the statistical information in official reports on CDM is based either on project documents or on surveys of projects.

The assessment of the CDM in the peer-reviewed literature is more cautious and pessimistic than UNFCCC, and two reviews (Olsen, 2007; Michaelowa and Michaelowa, 2011) contend that the current CDM design is neither pro-poor nor contributes to sustainable development. Shortcomings include obstacles and ethical dilemmas in carbon trading (Liverman, 2009; Newell and Bumpus, 2012), difficulties with implementation (Borges da Cunha *et al.*, 2007; Minang *et al.*, 2007; Gong, 2010), and procedural limitations (Lund, 2010). Case studies suggest that CDM may favor carbon offset goals over poverty reduction goals (Wittman and Caron, 2009), undermine local and non-governmental voices (Shin, 2010; Corbera and Jover, 2012), compete with the informal sector (Newell and Bumpus, 2012), and accentuate uneven development by threatening local livelihood security (Boyd and Goodman, 2011). Only a few CDM programs have shown positive impacts for poor communities, such as one in Peru that enhanced health and employment (Boyd and Juhola, 2009) and some in India supporting community-designed plans to strengthen participation of marginalized groups (Subbarao and Lloyd, 2011; Boyd and Goodman, 2011).

13.3.1.2. Reduction of Emissions from Deforestation and Forest Degradation (REDD+)

Reducing emissions through carbon forestry as part of UN REDD+ may adversely affect the livelihoods of poor people. Experience with forest carbon projects to date is inadequate to permit broad generalizations about the effects of REDD+ on livelihoods and poverty (Cotula *et al*., 2009; Hayes and Persha, 2010; Springate-Baginski *et al*., 2010). In a study of 20 forest carbon projects in Latin America, Africa and Asia, only five had conducted some form of assessment of the outcomes or impacts, demonstrating a lack of rigor in project evaluation (Caplow *et al*., 2011).

Some studies show favorable results in terms of poverty alleviation (Ferraro *et al*., 2011) and are optimistic about REDD+ (Kanowski *et al*., 2011; Rahlao *et al*., 2012) but raise concerns about its future developments (Hodgdon *et al*., 2012; Rana *et al*., 2012). Others have voiced concerns about negative impacts on the poor (Phelps *et al*., 2010; Larson, 2011; Van Dam, 2011; McDermott *et al*., 2011; Börner *et al*., 2011; Rahlao *et al*., 2012; Neupane and Shrestha, 2012; Mahanty *et al*., 2012) and on indigenous peoples (Shankland and Hasenclever, 2011). Latent negative impacts include exclusion of local populations from forest use, and the undermining of local ownership in the processes of documenting the state of their forests due to external monitoring and verification mechanisms (Gupta *et al*., 2012). Benefit flows may be unevenly distributed with regards to ethnicity (Krause and Loft, 2013), gender (UN-REDD, 2011; Peach Brown, 2011) or simply not target the poor (Hett *et al*., 2012). Also, the absence of a global REDD+ mechanism means that progress on REDD+ may occur as much through voluntary bilateral and public-private processes as through multilateral, regulatory requirements (Agrawal *et al*., 2011). Without a global agreement and mandated emissions reductions, the price of carbon will remain uncertain and vary greatly across different carbon forestry projects (Bailey *et al*., 2011), to the advantage of carbon credit buyers rather than the poor.

The 2010 Cancun Agreements highlight safeguards for governments to observe in REDD+ implementation, such as respect for the interests, knowledge, rights, and sustainable livelihoods of local communities and indigenous people. The extent to which these safeguards will be observed in practice is unclear due to the early implementation state of REDD+ in most countries as well as the uncertainty of the future of the global carbon market (Lohmann, 2010).

13.3.1.3. Voluntary Carbon Offsets

The voluntary carbon offset (VCO) market is significant from a livelihoods and poverty perspective because it typically targets smaller projects and may be better at reaching poor communities, though it is modest in size compared to the regulated market (~ 1%). Also, those involved in the VCO market, namely individuals, companies, organizations, and countries that have not ratified the Kyoto Protocol, are often more willing to pay for carbon offsets with co-benefits such as poverty alleviation (MacKerron *et al*., 2009).

Activities under VCO are dominated by renewable energy, primarily wind power (30%), forestation projects, including REDD (19%), and methane destruction in landfills (7%) (Peters-Stanley and Hamilton, 2012). It is too early to tell whether these VCO projects are successful in terms of poverty alleviation and other social goals, and results to date are highly mixed (Jindal *et al*., 2008; Swallow and Meinzen-Dick, 2009; Jindal, 2010; Estrada and Corbera, 2012; Stringer *et al*., 2012). Reported benefits include livelihood diversification, increased disposable income, biodiversity conservation, and strengthening local organizations, while exacerbated inequalities and loss of access to local resources are known negative impacts (Estrada and Corbera, 2012). A study in Kenya, Senegal, and Peru shows reduced losses of soil fertility in three soil carbon sequestration projects, but also the inability of the poorest farmers to participate and only marginal impacts on poverty reduction (Antle and Stoorvogel, 2009). Out of 78 projects in 23 countries in sub-Saharan Africa, only one promoted local social, economic, and environmental benefits while the rest focused mainly on efficiency of emission reductions (Karavai and Hinostroza, 2013).

13.3.1.4. Biofuel Production and Large-Scale Land Acquisitions

Biofuel production, often linked to large-scale transnational land acquisitions (LSLA), constitutes a mitigation response that raises two major livelihoods and poverty concerns: food price increases and dispossession of land (see Chapters 4, 9). LSLA have soared since 2008 (Von Braun *et al*., 2009; Deininger *et al*., 2011; Borras Jr *et al*., 2011), partly linked to climate change responses (*high agreement*). Production of biofuels is considered the primary driver, but there may be links to climate change through increasing food prices (Daniel, 2011), food insecurity (Robertson and Pinstrup-Andersen, 2010; Rosset, 2011; Sulser *et al*., 2011), and the potential that carbon markets, e.g. REDD+, may increase land prices (Cotula *et al*., 2009; Zoomers, 2010; Anseeuw *et al*., 2012). According to Anseeuw (2012), LSLA goals globally are primarily biofuels (40%), food (25%) and forestry (3%), with significant regional variation. The recent IPCC special report on renewable energy highlighted the uncertainties around the role of biofuels in food price increases and risks of deteriorating food security with future deployment of bioenergy (Edenhofer *et al*., 2011).

Increasing demand for biofuels shifts land from food to fuel production, which may increase food prices (Collier *et al*., 2008), disproportionally affecting the poor (Von Braun and Ahmed, 2008; Ruel *et al*., 2010; Bibi *et al*., 2010). Despite high agreement that biofuel production plays a role in food prices, little consensus exists on the size of this influence. Statistical analyses of the influence of biofuels on the 2007/08 food price increase range from 30% (Von Braun and Ahmed, 2008) to 70% (Mitchell, 2008), while economic modeling suggests a smaller direct role (<30%) (Aksoy and Isik-Dikmelik, 2008; Elobeid and Hart, 2008; Baffes and Haniotis, 2010; Ajanovic, 2011). Several studies link the 2007/08 price spike to speculation in agricultural futures markets (Runge and Senauer, 2007; Gilbert and McLeman, 2010; Ghosh, 2010) driven partly by potential future profits from biofuels (Trostle *et al*., 2011).

LSLA have also triggered a land rush in LICs, which affects livelihood choices and outcomes. New competition for land dispossesses smallholders, displaces food production, degrades the environment, and pushes the poor onto more marginal lands less adaptable to climatic stressors (Cotula *et al*., 2009; Borras Jr *et al*., 2011; Rulli *et al*., 2013; Weinzettel *et al*., 2013). The expansion of bioenergy, and biofuels in particular, increases the corporate power of international actors over governments and local actors with harmful effects on national food and agricultural policies (Dauvergne and Neville, 2009; Glenna and Cahoy, 2009; Hollander, 2010; Mol, 2010; Fortin, 2011; Jarosz, 2012), further marginalizing smallholders (Ariza-Montobbio *et al*., 2010; De Schutter, 2011; Neville and Dauvergne, 2012). There is growing apprehension that increased competition for scarce land undermines women's access to land and their ability to benefit economically from biofuel investment (Molony, 2011; Arndt *et al*., 2011; Chu, 2011; Julia and White, 2012; Behrman *et al*., 2012; Perch *et al*., 2012). Concerns differ to some extent among regions, with the greatest risk for negative outcomes for smallholders in Africa (Borras *et al*., 2011).

Mainstream economic modeling suggests optimism that biofuels may boost investment, employment, and economic growth, in LICs such as Mozambique (Arndt *et al*., 2009) and MICs such as India (Gopinathan and Sudhakaran, 2011) and Thailand (Silalertruksa *et al*., 2012), yet limited evidence exists on potential benefits being realized. A major government initiative to promote jatropha cultivation in India has failed (Kumar *et al*., 2011) and in some cases has left rural people worse off (Bastos Lima, 2012) whereas in Malawi it offered supplemental livelihood opportunities (Dyer *et al*., 2012) . Even though income and employment in Brazil may have increased due to ethanol production (Ferreira and Passador, 2011), structural inequalities in the sector remain (Peskett, 2007; Hall *et al*., 2009; Bastos Lima, 2012). Biofuel production in itself will not transform living conditions in rural areas without being integrated into development policies (Hanff *et al*., 2011; Jarosz, 2012; Dyer *et al*., 2012).

13.3.2. Impacts of Adaptation Responses on Poverty and Livelihoods

Even well-intentioned adaptation projects (see Chapters 14-16) and efforts may have unintended and sometimes detrimental impacts on livelihoods and poverty, and may exacerbate existing inequalities. This section assesses the effects of autonomous and planned adaptation and formal insurance schemes on the livelihoods of poor populations.

13.3.2.1. Impacts of Autonomous and Planned Adaptation Strategies on Livelihoods and Poverty

Autonomous adaptation strategies, such as diversification of livelihoods (Smith *et al*., 2000; Mertz *et al*., 2009), migration (McLeman and Smit, 2006; Tacoli, 2009) (see Chapter 12), storage of food (Smit and Skinner, 2002; Howden *et al*., 2007), communal pooling (Linnerooth-Bayer and Mechler, 2006), market mechanisms (Halstead and O'Shea, 2004), saving, credit societies, and systems of mutual support (Andersson and Gabrielsson, 2012) have been found to have positive effects on poverty reduction in certain contexts, or at least prevent further deterioration as a result of a weather events and climate, especially when supported by policy measures (Adger *et al*., 2003; Urwin and Jordan, 2008; Stringer *et al*., 2009). Yet, some autonomous strategies such as diversification and storage are often unavailable to the poorest, who lack the required resources or surplus (Smithers and Blay-Palmer, 2001; Osbahr *et al*., 2008; Seo, 2010). In some cases, risk reduction strategies involve a trade-off with higher-income options (Hazell and Hess, 2010; Alpizar *et al*., 2011; Benson *et al*., 2012). Moreover, autonomous adaptation strategies can increase vulnerability for others or be subject to local elite capture (McLaughlin and Dietz, 2008; Bhattamishra and Barrett, 2010). For example, richer farmers in Mozambique with access to irrigation benefited from higher producer prices and ready availability of casual labor from poorer farmers during the 2002/03 drought (Eriksen and Silva, 2009). There is no evidence regarding the effect of autonomous responses of the poor in MICs and HICs.

Few rigorous assessments of the effects of pilot adaptation projects exist outside of organizations' own assessments (Mapfumo *et al*., 2010; Nkem *et al*., 2011) or evaluations of the extent to which planned adaptation activities have been implemented or integrated into development (Gagnon-Lebrun and Agrawala, 2006; Gigli and Agrawala, 2007). An assessment of the only completed GEF/WB-funded adaptation project, in the Caribbean, Colombia, and Kiribati, did not directly appraise the effects on poverty and livelihoods. Other projects, though, such as in India's Karnataka Watershed, increased agricultural productivity, income, and employment, benefiting the poorest and landless and improving equity (IEG, 2012). New insights emerge from ecosystem-based adaptation (see Chapters 15, 16).

13.3.2.2. Insurance Mechanisms for Adaptation

Insurance mechanisms (see Glossary) reflect the tendency that some formal adaptation measures reach the wealthier more easily while prohibitive costs may prevent poor people from accessing such mechanisms. Nonetheless, public and private insurance systems have been proposed by the World Bank and UNFCCC as an adaptation strategy to reduce, share, and spread climate change-induced risk and smooth consumption, especially among poor households (Mechler *et al*., 2006; Hertel and Rosch, 2010; Akter *et al*., 2011; Benson *et al*., 2012). Formal insurance schemes can potentially provide a way out of poverty traps (Barnett *et al*., 2008) caused by the years-long process for a household to rebuild assets after climate shocks (Dercon, 2006; Hertel and Rosch, 2010).

Poor people tend not to be insured via formal institutions, though strategies such as risk spreading, social networks, local credit, asset markets, and dividing herds between kin act as informal risk management mechanisms (Barnett *et al*., 2008; Pierro and Desai, 2008; Giné *et al*., 2008; Hertel and Rosch, 2010). Unable to access insurance, poor people are often forced to invest in low-risk, low-return livelihood activities, which makes accumulating assets to escape chronic poverty very difficult (Elbers *et al*., 2007; Barnett *et al*., 2008). As a response, new insurance mechanisms such as micro-insurance directed at low-income people, and weather index insurance for crops and livestock, have emerged, but have shown mixed results (Barnett *et al*., 2008; Mahul *et al*., 2009; Akter *et al*., 2011; Matsaert *et al*., 2011; Biener and Eling, 2012). Experiences from South Asia and several African countries illustrate positive effects of micro-insurance although affordability may limit the potential for the poorest (Yamauchi *et al*., 2009; Hochrainer-Stigler *et al*., 2012). Another reason for the slow uptake is that farmers may not fully understand the merits and function of the new insurance schemes (Giné and Yang, 2009; Patt *et al*., 2010).

13.4. Implications of Climate Change for Poverty Alleviation Efforts

This section considers the implications climate change has for poverty alleviation efforts and what they may mean for current and future pathways for sustainable development. Evidence from observed and projected interactions between climate, poverty reduction, and development highlights how addressing climate change and poverty may

result in diminished success or productive synergies with respect to eradicating poverty, managing risk, pursuing sustainable development, and designing climate-resilient pathways, which are "evolutionary processes for managing change within complex systems to reduce disruptions and enhance opportunities" (see Glossary). This section builds on the findings from 13.1 to 13.3 and stresses the need to attend to the complexity of livelihood dynamics, multi-dimensional poverty, and intersecting inequalities to successfully navigate climate-resilient development pathways.

Observed impacts of weather events and climate on livelihoods and poverty and impacts projected from the sub-national to the global level suggest that livelihood resilience, poverty alleviation, and development are already undermined and will continue to be eroded into the future (*high confidence*). Climate change will slow down the pace of poverty reduction, jeopardize sustainable development, and further erode food security (*high confidence*) (Stern, 2009; Hope, 2009; Thurlow *et al.*, 2009; Iglesias *et al.*, 2011; Skoufias *et al.*, 2011b). Currently poor and food-insecure regions will continue to be disproportionately affected into the future (*high agreement*) (Challinor *et al.*, 2007; Lobell *et al.*, 2008; Assuncao and Cheres, 2008; Liu *et al.*, 2008; Thornton *et al.*, 2008; Menon, 2009; Jones and Thornton, 2009; Nordhaus, 2010; Jacoby *et al.*, 2011; Burke *et al.*, 2011; Skoufias *et al.*, 2011a; Adano *et al.*, 2012). Poorer countries will experience continued decline in adaptive capacity, which will hamper development (*high confidence*). Iglesias *et al.* (2011), for instance, project increasing inequality among continents in the case of progressively severe climate change scenarios. Posey (2009) highlights lower adaptive capacities in communities with greater concentrations of racial minorities and low-income households than in more affluent communities, due to multidimensional inequality and marginalization. Although there is *high agreement* about the heterogeneity of future impacts on poverty, few studies consider more diverse climate change scenarios (Skoufias *et al.*, 2011b) or the potential of four degrees and beyond (New *et al.*, 2011). The World Bank (2012b, p.65) states that "climate change in a four degree world could seriously undermine poverty alleviation in many regions."

13.4.1. Lessons from Climate-Development Efforts

Two key models have attempted to integrate climate and poverty concerns into development efforts: mainstreaming adaptation into development priorities and pro-poor adaptation (see also Chapters 14-16). Lessons from "adaptation as development," in which development is seen as the basis for adaptation, and "adaptation plus development," in which development interventions address future climate threats (Ayers and Dodman, 2010), typify the disagreement in policy spheres about what sustainability constitutes (Le Blanc *et al.*, 2012) and the practical gulf between climate change policy and development spheres (Ayers and Dodman, 2010). To date, observed and projected climate change impacts are not systematically integrated into poverty reduction programs, although such integration could result in substantial resilience to covariate and idiosyncratic shocks and stresses (Béné *et al.*, 2012). At the same time, science and policy emphasis on rapid-onset events, sectoral impacts, and poverty statistics has diverted attention from threats to sustainability and resilient pathways. Even where legal reforms to secure the rights of the poor exist, as in Mexico's Climate Law, inequalities persist (MacLennan and Perch, 2012). Without addressing the climatic, social, and environmental stressors that shape livelihood trajectories, including poverty traps (see Figure 13-2), and the underlying causes of poverty, persistent inequalities, and uneven resource access and institutional support, adaption efforts and policies will be nothing more than temporary fixes. At the same time, poverty alleviation alone will not necessarily lead to more equality (Pogge, 2009; Milanovic, 2012). Box 13-2 provides insight into three examples.

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Box 13-2. Lessons from Social Protection, Disaster Risk Reduction, and Energy Access

Social protection (SP): Considerable challenges emerge at the intersection of climate change adaptation, disaster risk reduction, and social protection. SP programs include public and private initiatives that transfer income or assets to the poor, protect against livelihood risks, and raise the social status and rights of the marginalized (see Glossary). Cash transfer programs are among the principal instruments used by governments for poverty alleviation (Barrientos and Hulme 2008; Niño-Zarazúa 2010). There is *medium agreement* among scholars and practitioners that SP helps the chronically poor reduce risk and protect assets during crises (Devereux *et al.*, 2010; Barrientos, 2011; Dercon, 2011; Devereux *et al.*, 2011). However, at the regional and municipal level, SP does not address local government

capacity to ensure risk reduction by providing water, sanitation, drainage, health care, and emergency services. Also, SP does not strengthen local collective capacity to proactively address climate change risks and take action.

SP that supports pro-poor climate change adaptation and disaster risk reduction by strengthening the resilience of vulnerable populations to shocks is labeled "adaptive social protection" (ASP) (Davies *et al*., 2009). ASPs have almost exclusively focused on LICs and some MICs rather than on poor people in HICs. Few studies exist on the effectiveness of ASP for addressing incremental climatic changes and rapid-onset events, and the changing nature of climate risks, embedded in an understanding of dynamic livelihood trajectories (Heltberg *et al*., 2009; Arnall *et al*., 2010; Bee *et al*., 2013). For instance, the Productive Safety Net Program in Ethiopia, one of the more successful SPs, had positive effects on household food consumption and asset protection (Devereux *et al*., 2006; Slater *et al*., 2006). Yet, this and programs such as Brazil's *Bolsa Familia* and *Bolsa Verde* offer few concrete pathways to tackling systemic vulnerabilities and inequalities that inhibit effective responses to severe shocks, though they stress the role of local governments in addressing livelihood security and resilience in the long term rather than focusing on short-term disaster relief (Gilligan *et al*., 2009; Conway and Schipper, 2011; Béné *et al*., 2012; UNDP, 2012).

Disaster risk reduction (DRR): The development and application of DRR (see Glossary) has been among the most important routes for generating attention from local governments and civil society about the risks of extreme weather, and came to the fore as the concentration of disaster deaths from extreme weather in LICs and MICs became evident (United Nations 2009, 2011). Now, DRR is increasingly employed as an adaptation measure, for example through community-based climate risk reduction (Tompkins *et al*., 2008; Meenawat and Sovacool, 2011; McSweeney and Coomes, 2011; Field *et al*., 2012b) and has helped identify DRR roles for local governments (IFRC 2010). Yet, sometimes disaster management-oriented adaptation can favor property and investments of the relatively richer and divert attention and funding from measures that address the poor, as suggested in a case study of Vietnam (Buch Hansen, 2013). The effectiveness of DRR in supporting pro-poor climate change adaptation will depend on governance structures to address changing risk contexts in policies and investments while responding to the needs and priorities of their low-income population. Experiences from Hurricane Katrina and the Tōhoku earthquake and tsunami exhibit the additional and multiplier effect of a disaster on top of underlying structural inequalities. Their persistence years later, as shown with Katrina (Schwartz, 2007; Zottarelli, 2008; Fussell *et al*., 2010), further stresses the need for expanded analyses beyond the events themselves and the recognition of the many factors that perpetuate the vicious cycle of poverty, multidimensional deprivation, and inequality.

Energy access: Energy is critical for rural development (Barnes *et al*., 2010; Kaygusuz, 2011; Kaygusuz, 2012) and for alleviation of urban poverty (Parikh *et al*., 2012). One proposed climate-resilient pathway is to increase renewable energy use, which has the potential to boost energy access for billions of people who currently have no access to safe and efficient energy, while cutting GHG emissions from rising non-renewable energy consumption (Casillas and Kammen, 2010; Edenhofer *et al*., 2011). Benefits include better health (see Chapter 11), employment, and cost savings relative to fossil fuels (Edenhofer *et al*., 2011; Jerneck and Olsson, 2012). Yet, *limited evidence* exists that renewable energy creates more jobs than conventional energy (Karakezi *et al*., 2006; Akella *et al*., 2009).

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13.4.2. Toward Climate-Resilient Development Pathways

Given the multiple challenges at the climate-poverty-development nexus, debates increasingly focus on transforming the development pathways themselves toward greater social and environmental sustainability, equity, resilience, and justice, calling for a fundamental shift toward climate-resilient development pathways (see Chapter 20). This perspective acknowledges the major shortcomings in dominant global development pathways, above all rising levels of consumption and emissions, privatization of resources, and limited capacities of local governments and civil society to counter these trends (Pelling, 2010; Eriksen *et al*., 2011; O'Brien, 2012; UN, 2012a).

At Rio+20 in 2012, an Open Working Group was created by the UN General Assembly to develop Sustainable Development Goals (SDGs) building on the Millennium Development Goals (MDGs), which are criticized for not explicitly addressing the root causes of poverty, inequality, or climate change (Melamed, 2012; UN, 2012b) and the

anticipated failure to reach MDG 1 (eradicate extreme poverty and hunger by 2015), with or without climate change (Tubiello *et al*., 2008). Early SDG debates reveal a stronger focus on eradicating extreme poverty and environmental problems facing the poor (UN, 2012a). This framing of development acknowledges shared global futures that require collective action from the richest, not merely promoting welfare for the poorest, to address both climate change and poverty (Ayers and Dodman, 2010; UN, 2012a; UN, 2012b). Little information exists to date to project how these SDGs will support climate-resilient development pathways. Formulating goals, however, will not suffice unless the global institutional framework for sustainable development is radically reformed (Biermann *et al*., 2012).

Paying attention to dynamic livelihoods and multidimensional poverty and the multifaceted impacts of climate change and climate change responses is central to achieving climate-resilient development pathways (see Chapter 20). Evidence from sections 13.2 and 13.3 suggests that increasing global inequality, new poverty in MICs and HICs, and more people shifting from transient to chronic poverty overlaid with business-as-usual development and climate policies, will bring the poor and the marginalized precariously close to the two most undesirable future scenarios as conceptualized in the shared socio-economic pathways (SSPs) (see Figure 20-2): social fragmentation (fragmented world) and inequality (unequal world). At the community level, inadequate governance structures and elite capture often propel less affluent households into deeper poverty. There is *high agreement* among scholars of global governance that fragmentation also exists at the level of the global climate regime (Biermann, 2010; Roberts, 2011; Mol, 2012), rooted in deep and entrenched inequalities (Parks and Roberts, 2010). The extent to which fragmentation promotes positive or negative outcomes of climate and development goals is contested, ranging from polycentric governance modes (Ostrom, 2010) to conflictive fragmentation (Biermann *et al*., 2009; Mittelman, 2013). Evidence from this chapter demonstrates that, in order to move toward the SSP1 (sustainability), a fundamental rethinking of poverty and development is needed that emphasizes equity among the poor and non-poor to collectively address GHG emissions and vulnerabilities while striving toward a joint, just, and desirable future.

13.5. Synthesis and Research Gaps

Previous IPCC reports have stated that climate change would cause disproportionally adverse effects for the world's poor. However, they presented a rather generalized view that all poor people were vulnerable, in contrast to earlier scientific studies highlighting vulnerability as contextual with variation over time and space. This chapter is entirely devoted to exploring poverty in relation to climate change. It uses a livelihoods lens to assess the interactions between climate change and the multiple dimensions of poverty, not just income poverty. This lens also reveals how inequalities perpetuate poverty to shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. This chapter illustrates that climate change adds an additional burden to the multiple facets of poor people's lives and livelihoods. Moreover, it emphasizes that climate change may create new groups of poor people, not only in low-income countries but also in middle- and high-income countries. Neither alleviating poverty nor decreasing vulnerabilities to climate change can be achieved unless entrenched inequalities are reduced. This chapter concludes that climate change policy responses often do not benefit the world's poor, and highlights lessons for climate-resilient development pathways.

Eight major research gaps are identified with respect to the observed and projected impacts of climate change and climate change responses:

- Poverty dynamics are not sufficiently accounted for in current climate change research. Most research as well as poverty measurements remain focused on only one or two dimensions of poverty. Insufficient work assesses the distribution of poverty at the level of households, spatial and temporal shifts, critical thresholds that plunge some transient poor into chronic poverty, and poverty traps, in the context of climatic and non-climatic stressors. Many of these dynamics remain hidden, incompletely captured in poverty statistics and disaster and development discourses. Key assumptions in economic models (e.g., constant within-country distribution of per-capita income over time, linear relationship between economic growth and poverty headcounts) are ill-suited to capture local and sub-national poverty dynamics, confounding projections of future poverty levels.
- Though an abundance of studies exists that explore climate change impacts on livelihoods, the large majority does not focus on trajectories but only offers snapshots. In contrast to static representations, an

explicit exploration of livelihood dynamics reveals how people respond to a series of climatic stressors and shocks over time.

- Few studies examine how the structural inequalities, power imbalances, and intersecting axes of privilege and marginalization shape differential vulnerabilities to climate change. Although there is a growing body of literature on climate change and gender as well as on indigeneity, other axes such as age, class, race, caste, and (dis)ability, have been underexplored. Understanding how simultaneous and intersecting inequalities determine climate change impacts reveals which particular drivers of vulnerability are at play in one context, while absent in another.
- Very limited research examines climate change impacts on poor people and livelihoods in middle- to high-income countries. Despite mounting evidence of observed impacts of climatic events on the poor in MICs and HICs, as documented for the European heat wave, Hurricane Katrina in the U.S., and the ten-year drought in Australia, the majority of research on the poverty-climate nexus remains focused on the poorest countries.
- There remains a lack of rigorous data collection and analysis with respect to 'small' disasters in poor people's lives. This gap leads to significant underestimation of lived experiences with climate change, in which particular loss and harm remain largely undetected. There is a need for more climatology research informed by the needs of vulnerable livelihoods, for instance on the effects of changing winds as a combined result of climate change and land cover change, and their effects on increasing evaporation and water availability.
- Not enough consideration is given to the "long tails" in terms of extreme stressors and shock events, such as the potential of four degrees and beyond, underestimating the range of possible impacts on the poor and marginalized.
- There is a lack of in-depth research on the direct and indirect effects of mitigation and adaptation climate-related policies such as CDM, REDD+, biofuels, and insurance, on livelihoods, poverty, and inequality. More in-depth research has the potential to improve the capacity of these policies to become pro-poor.
- Limited understanding exists of how poverty alleviation and more equality between the poor and the non-poor are best built into climate-resilient development pathways in order to strive toward a just and desirable future for all.

Frequently Asked Questions

FAQ 13.1: How important are climate change-driven impacts on poverty compared to other drivers of poverty?

Poverty is a complex social and political problem, intertwined in numerous ways with processes of socioeconomic, cultural, institutional, and political marginalization, inequality, and deprivation, in low-, medium-, and high-income countries. Climate change intersects with the multidimensional facets of poverty to drive not only income poverty but also undermine wellbeing, agency, and a sense of belonging. This complexity makes measuring impacts and attribution to climate change exceedingly challenging. Even modest changes in seasonality of rainfall, temperature, and wind patterns, as observed for instance among climate-sensitive livelihoods in high mountain environments, drylands, and the Arctic, and in informal settlements and urban slums, can push transient poor and marginalized people over a critical threshold into chronic poverty as they lack access to effective response options. Impacts of extreme events, such as floods, droughts, and heat waves, especially when occurring in a series, can significantly erode poor people's assets and further undermine their protection in terms of labor, housing, infrastructure, and social networks. Indirect impacts, such as increases in food prices due to climate-related disasters and/or policies, can also harm the poor, including the urban poor who are net buyers of food.

FAQ 13.2: How do multiple stressors interact with dynamic livelihoods and structural inequalities?

Multiple stressors, or factors such as shifts in seasons and market volatility, interact and reinforce each other to affect livelihood opportunities and decision making. A variety of stressors and opportunities emerge from macro-level forces such as climate change, globalization, and technological change, as well as from conditions such as politics and infrastructure at the regional, national, and local levels. Institutions, policies, and decision making mediate which stressors result in shocks for particular livelihoods and households. Moreover, structural inequalities amplify and compound the effects of these stressors, especially for livelihoods and households with limited asset flexibility and/or those who experience inequalities and marginalization along the axes of gender, age, class, race,

indigeneity, and (dis)ability. The dynamic interplay between weather events and climate, institutions, and livelihoods is socially differentiated, allowing virtuous cycles and positive trajectories for some and vicious cycles and downward trajectories for others, at particular points in time. For instance, a women-headed household from the lowest caste in Nepal may struggle to satisfy additional labor demands to produce drought-resistant subsistence crops and fulfill sharecropping contracts to the high caste landlord while more affluent men-headed households from this high caste may benefit from shifting seasonal precipitation patterns and new local market opportunities.

[INSERT FIGURE 13-5 HERE

Figure 13-5: Multiple stressors related to climate change, globalizations, and technological change interact with national and regional institutions to create shocks to place-based livelihoods. Inspired by transition theory (Geels, 2011).]

FAQ 13.3: Are there unintended negative consequences of climate change policies for people who are poor?

Policies related to climate change mitigation and adaptation may have unintended and potentially detrimental effects for poor people and their livelihoods. Climate-related policies have compound consequences. For example, the recent rapid increase in large-scale land acquisitions emerged, at least partially, as a result of climate change mitigation policies to promote biofuels, as well as a growing concern about food security in high- and middle-income countries. Conversion of presumably marginal or idle land in countries in Africa, Latin America, and Southeast Asia has contributed to food price increases and also has displaces smallholders' croplands. Poor urban residents are particularly vulnerable to food price increases as they use a large income share to purchase food while some agricultural self-employed groups may actually benefit from increased food prices. Besides stress on food security, other adverse consequences of biofuels have been reported for poor and marginalized people, including declining biodiversity, competition for water, and unfavorable shifts in access to and control over resources, often to the detriment of women farmers and other disadvantaged groups. However, in some cases, men and women who find employment in the biofuel industry acknowledge opportunities to participate in the cash economy.

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Table 13-1: Gendered impacts of Australia's ten-year drought.

Impacts	*For men*	*For women*
Increased workload	Heartbreaking and physically demanding tasks include feeding livestock, carting water, destroying frail animals	Increased work includes assisting with farm tasks and working off the farm for additional income
Community effects	Locked into farms, loss of political power	Increased interactions and caregiving work, taking care of others' health at the expense of their own
Psychological toll	Feel demonized (farmers responsible for crisis), increased stress, social isolation, depression, and high suicide levels	Working lives appear indefinite, and increased stress

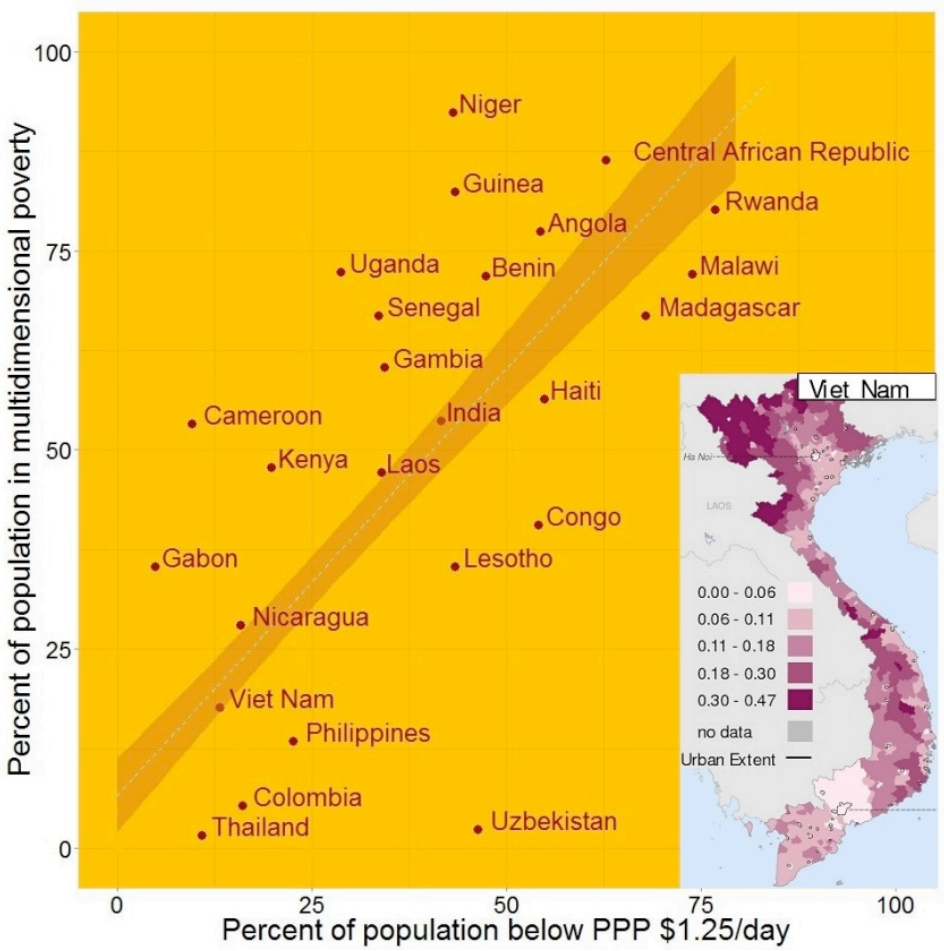
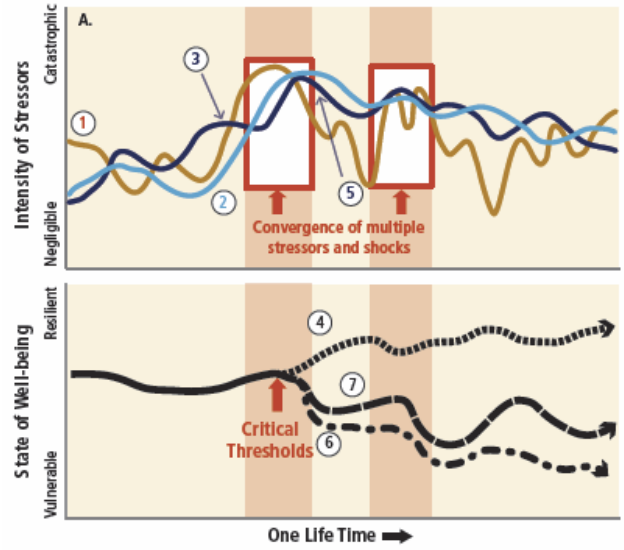
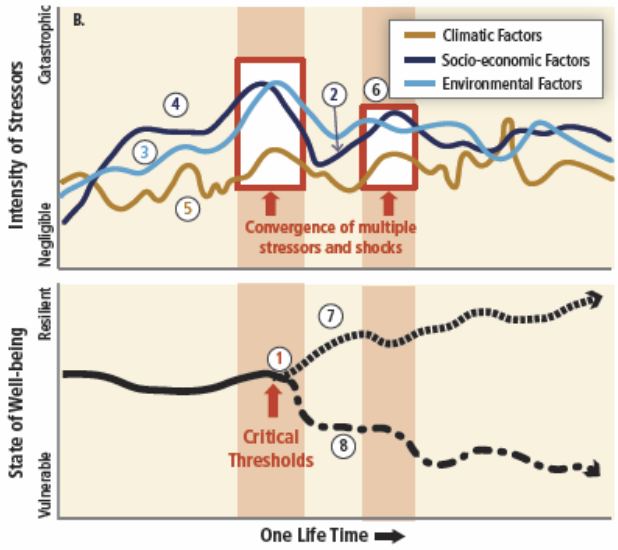


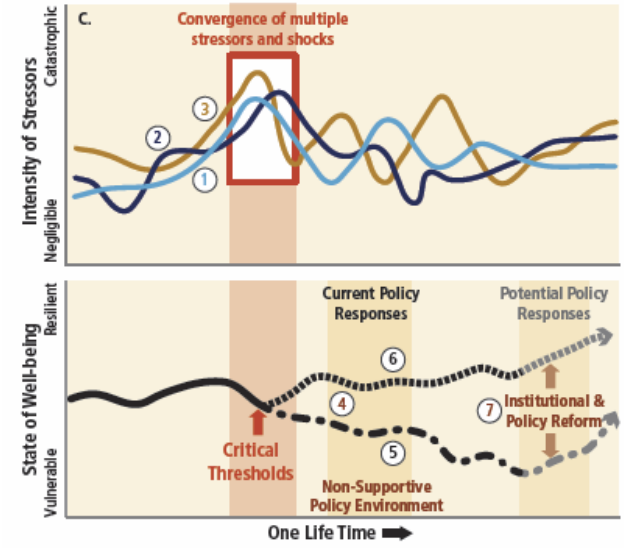
Figure 13-1: Multidimensional poverty and income poverty, with linear regression relationship (dotted line) and shaded 95% confidence interval based on 96 countries (HDR, 2011). The map inset shows the Poverty Gap Index score in Viet Nam, aggregated at district level, expressed as ratio of poverty line of yearly expenditure per capita).



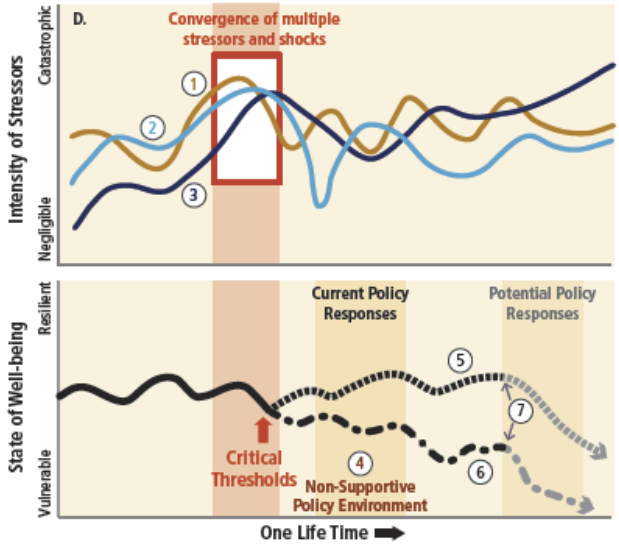
A. Botswana's drylands (Sallu et al., 2010). Over the past 30 years, rural households have faced 1) droughts, late onset and increased unpredictability of rainfall, and frost, 2) drying of Lake Xau, and land degradation. Households responded differently to these stressors, given their financial and physical assets, diversification of and within livelihood activities, family relations, and institutional and governmental support. Despite 3) weakening of social networks and declining livestock due to lack of water, distinct livelihood trajectories emerged. 4) "Accumulators" were often able to benefit from crises, for instance through access to salaried employment or 5) new hunting quotas, while 6) "dependent" households showed a degenerative trajectory, losing more and more livelihood assets, becoming reliant on governmental support after another period of convergent stressors. 7) "Diversifiers" had trajectories fluctuating between vulnerable and resilient states.



B. Coastal Bangladesh (Pouliotte et al., 2010) 1) Households in Surbarnabad have faced a critical threshold and shifted from rice and vegetable cultivation to saltwater shrimp farming, 2) which has grown due to a strong export market and international donor and national government support. This shift is a result of a combination of environmental and socio-economic factors, out of which climatic stressors appear to only play a minor role: 3) saltwater intrusion due to 4) the construction and poor management of the Bangladeshi Coastal Embankment Project, the construction of a dam in India, local water diversions, 5) and sea level rise and storm surges. The conversion to shrimp farming 6) has caused rising disease levels and 7) concentrated wealth and power for the more affluent families while 8) further diminishing the livelihood options for the poor who lack the resources to grow crops in salinated water and lose grazing areas and dung from formerly accessible rice fields.



C. Mountain environments (McDowell & Hess, 2012). Indigenous Aymara farmers in highland Bolivia face land scarcity, pervasive poverty, climate change, and lack of infrastructure due in part to racism and institutional marginalization. 1) The retreat of the Mururata glacier causes water shortages, compounded by 2) the increased water requirements of cash crops on smaller and smaller "minifundios" and market uncertainties. 3) High temperatures amplify evaporation, and flash floods coupled with delayed rainfall cause irrigation canals to collapse. 4) The current policy environment makes it difficult to access loans and obtain land titles, 5) pushing many farmers onto down-ward livelihood trajectories while 6) those who can afford it invest in fruit and vegetable trees at higher altitudes. 7) Sustained access to land, technical assistance, and irrigation infrastructure would be vital policy responses to enhance wellbeing.



D. Urban flooding in Lagos (Adelekan, 2010). Flooding threatens the livelihoods of people in Lagos, Nigeria, where >70 percent live in slums. 1) Increased severity in rainstorms, sea level rise, and storm surges, coupled with 2) the destruction of mangroves and wetlands, disturb people's jobs as traders, wharf workers, and artisans, while destroying physical and human assets. 3) Poor urban management, lacking infrastructure for water supply, and inadequate stormwater drainage have not kept up with urban growth. 4) Inadequate policy responses, including uncontrolled land reclamation, make these communities highly vulnerable to flooding. 5) Only some residents can afford sand and broken sandcrete blocks. 6) Livelihood conditions in these slums are expected to further erode for most households. 7) Given policy priorities for the construction of high-income residential areas, current residents fear eviction.

Figure 13-2: Livelihood dynamics under simultaneous climatic, environmental, and socioeconomic stressors and shocks leading to differential risk spaces and livelihood trajectories over a lifetime.

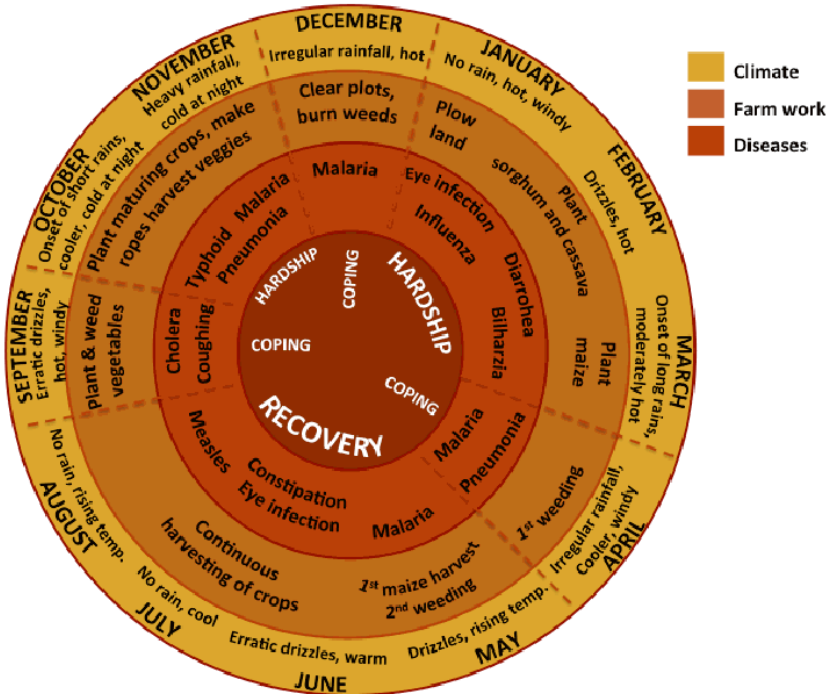


Figure 13-3: 'Wheel of hardship' – a generalized seasonal calendar depicting livelihood conditions and stress based on experiences of smallholder farmers in the Lake Victoria Basin in Kenya and Tanzania (Gabrielsson *et al.*, 2012).

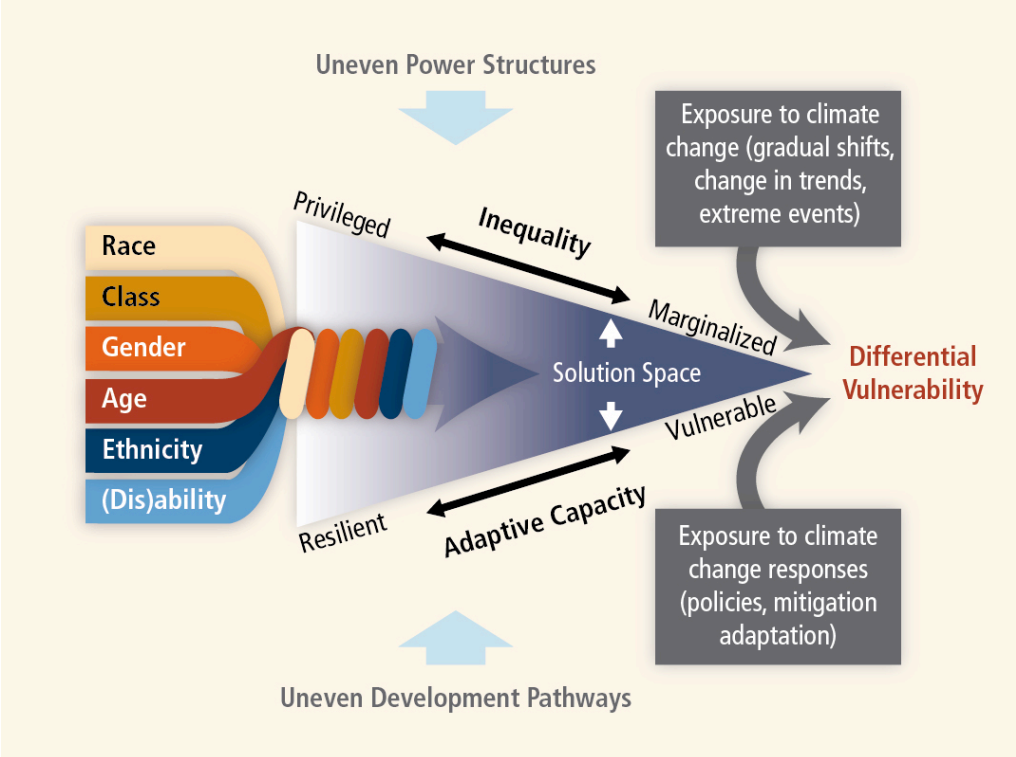


Figure 13-4: Intersecting dimensions of inequality.

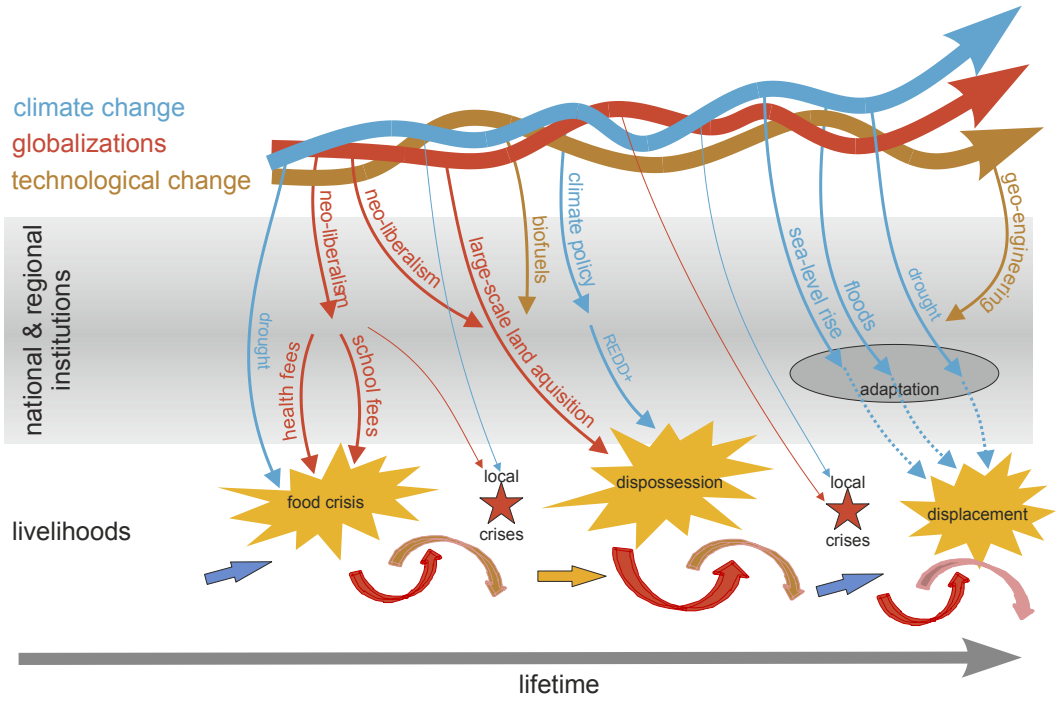


Figure 13-5: Multiple stressors related to climate change, globalizations, and technological change interact with national and regional institutions to create shocks to place-based livelihoods. Inspired by transition theory (Geels, 2011).

Chapter 14. Adaptation Needs and Options

Coordinating Lead Authors
Ian Noble (Australia), Saleemul Huq (Bangladesh)

Lead Authors
Yury Anokhin (Russian Federation), JoAnn Carmin (USA), Dieudonne Goudou (Niger), Felino Lansigan (Philippines), Balgis Osman-Elasha (Sudan), Alicia Villamizar (Venezuela)

Contributing Authors
Jessica Ayers (UK), Frans Berkhout (Netherlands), Kirsten Dow (USA), Hans-Martin Füssel (Germany), Joel Smith (USA), Kathleen Tierney (USA)

Review Editors
Anthony Patt (Austria), Kuniyoshi Takeuchi (Japan)

Volunteer Chapter Scientist
Eric Chu (USA)

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Executive Summary

Since AR4 the framing of adaptation has moved further from a focus on biophysical vulnerability to the wider social and economic drivers of vulnerability (*high agreement, robust evidence*). These include the gender, age, health, social status and ethnicity of individuals and groups and the political system in place within a region and country. [14.1, 14.2]

An emphasis continues to be placed on engineered and technological adaptation options, but there is growing awareness of the need for ecosystem-based, institutional, and social measures, including the provision of climate-linked safety nets for those who are most vulnerable (*high agreement, robust evidence*). Adaptation measures are increasing and becoming more integrated within wider policy frameworks. Integration streamlines the adaptation planning and decision making process and embeds climate sensitive thinking in existing and new institutions and organizations. This helps avoid mismatches with development planning, facilitates the blending of multiple funding streams and reduces the possibility of maladaptive actions. [14.3]

Approaches to selecting adaptation options continue to emphasize minimizing costs, achieving co-benefits, and incremental change, but there is increasing recognition that transformative changes may be necessary in order to prepare for climate impacts (*medium agreement, medium evidence*). While no-regret, low-regret and win-win strategies have attracted most attention in the past, there is increasing recognition that an adequate adaptive response will mean acting in the face of continuing uncertainty about the extent of climate change and the nature of its impacts. While attention to flexibility and safety margins is becoming more common in selecting adaptation options, many see the need for more transformative changes in our perception and paradigms about the nature of climate change, adaptation and their relationship to other natural and human systems. [14.1, 14.3.4]

Among the many actors and roles associated with adaptation two are increasingly recognized as critical to progress; namely those associated with local governance and those with the private sector (*high agreement, medium evidence*). These two groups will bear the main responsibility for translating the top-down flow of risk information and financing, and in scaling up the bottom-up efforts of communities and households in planning and implementing their selected adaptation actions. Local institutions, including local governments, NGOs and civil society organisations, are among the key actors in adaptation but are often limited by lack of resources and capacity. [14.4.2, 14.4.3] Private entities, from individual farmers and SMEs (small to medium enterprises) to large

corporations, will seek to protect their production systems, supply lines and markets, by pursuing adaptation related opportunities. These goals will help expand adaptation activities but they may not align with government or community priorities without coordination and incentives. [14.4.8]

Adaptation assessments continue to evolve leading to a general awareness among decision makers and stakeholders of climate risks and adaptation needs and options, however, this is often not translated into the implementation of even simple adaptation measures within ongoing activities or risk management planning (the 'adaptation bottleneck') (*high agreement, medium evidence*). Most of the assessments of adaptation done so far have been restricted to impacts, vulnerability and adaptation planning, with very few assessing the processes of implementation and evaluation of actual adaptation actions [14.5.1]. Assessments that include include both top-down assessments of biophysical climate change risks and bottom-up assessments of what makes people vulnerable to those risks will help to deliver local solutions to globally derived hazards (the 'adaptation paradox'). Also, assessments that are linked more directly to particular decisions and that provide information tailored to facilitate the decision making process and best suited to delivering effective adaptation measures and overcoming the 'adaptation bottleneck' [14.5.3

Evaluation of adaptation effectiveness is still in its infancy (*high agreement, medium evidence*). Experience in selecting metrics to identify adaptation needs and to measure effectiveness is increasing. [14.6.2, 14.6.3] But the search for metrics for adaptation will remain contentious with multiple alternatives competing for attention as governments, institutions, communities and individuals value needs and outcomes differently and many of those values cannot be captured in a comparable way by metrics. [14.6.4] The demand for metrics to measure adaptation needs and effectiveness is increasing as more resources are directed to adaptation. These indicators need to track not just process and implementation, but also the extent to which targeted changes are occurring. [14.6.2.3]

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change (*high agreement, medium evidence*). [14.7.3] The definition of maladaptation used in AR5 has changed subtly to recognize that maladaptation arises not only from inadvertent badly planned adaptation actions, but also from deliberate decisions where wider considerations place greater emphasis on short-term outcomes ahead of longer-term threats, or that discount, or fail to consider, the full range of interactions arising from the planned actions. [14.7.1]

14.1. Introduction

The rapid pace of climate change and its associated impacts means that we must adapt. In AR5, adaptation is defined in the following way, "In human systems, the process of adjustment to actual or expected climate and its effects, which seeks to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate." The distinction between human and natural systems directs our attention to differences in planned and unplanned adaptation. Natural systems have the potential to adapt through evolutionary processes, although humans may intervene to promote particular adjustments. In contrast, adaptation in human systems requires intentionality and therefore, is the result of planned efforts to address needs and advance options. Coping behavior remains common, such as in instances where immediate actions are taken to prepare for and respond to natural hazards and other extreme events. However, as individuals, communities, and governments account for and take initiatives to address actual and expected climate impacts, they are engaging in planned modes of adaptation.

A further classification that is becoming increasingly important in negotiations and implementation, and integral to AR5, is between incremental and transformational adaptation. The former refers to actions where the central aim is to maintain the essence and integrity of incumbent socio-economic systems and institutions, such as incremental adjustments to cropping systems through new varieties and more efficient irrigation. Alternatively, transformational adaptation seeks to change the fundamental attributes of systems in response to actual or expected climate and its effects. It includes not just changes in activities, such as changing from cropping to livestock or migrating to take up cropping elsewhere, but also changes in our perception and paradigms about the nature of climate change,

adaptation and their relationship to other natural and human systems (Kates *et al.,* 2012; IPCC SREX, 2012, Section 8.6.2.3). Differentiation between these two perspectives is essential since it affects how we approach adaptation, how we integrate it into planning and policy, and how we allocate adaptation funding in both developed and developing countries.

This chapter establishes a foundation for understanding adaptation by reviewing core concepts related to adaptation, with a focus on mapping out broad categories of needs and options. Adaptation needs refer to circumstances requiring action to ensure safety of populations and security of assets in response to climate impacts while adaptation options are the array of strategies and measures available and appropriate to address needs. Since identifying needs and selecting and implementing options requires the engagement of individuals, organizations, and governments at all levels, this chapter also considers the range of actors involved in these processes and summarizes the balance needed between adaptation and potential maladaptation. An ongoing theme throughout the chapter is the concept of mainstreaming or the integration of adaptation to climate change with other areas of government action and responsibility. This chapter also highlights some important tools in implementing adaptation, namely approaches to assessing needs at national, subnational and sectoral levels, and the challenges of applying metrics to determine adaptation needs and the effectiveness of adaptation actions. In the course of these discussions, this chapter establishes a foundation for the three adaptation chapters that follow. The existence of adaptation options does not necessarily mean that these options can be implemented when the need arises. Therefore, Chapter 15 examines adaptation planning and implementation, including the challenges faced and how these can be addressed. Chapter 16 focuses on adaptation opportunities and constraints while Chapter 17 assesses the economic costs and benefits of adaptation.

Summary of Key Findings from AR4

The Fourth Assessment Report (AR4) refined the basic terminology of adaptation and concluded that adaptation to climate change was already taking place, but on a limited basis. Societies have a long record of adapting to the impacts of weather and climate through a range of practices that include crop diversification, irrigation, water management, disaster risk management, and insurance, but climate change poses novel risks often outside the range of experience.

AR4 found that deliberate adaptation measures in response to anticipated climate change were being implemented by a range of public and private actors, on a limited basis, in both developed and developing countries. These measures are undertaken through policies, investments in infrastructure and technologies, and behavioral change, but they are seldom undertaken in response to climate change alone. Many actions that facilitate adaptation to climate change are undertaken to deal with current extreme events such as heat waves and cyclones and often embedded within broader sectoral initiatives such as water resource planning, coastal defense and disaster management planning.

AR4 concluded that there are individuals and groups within all societies that have insufficient capacity to adapt to climate change. The capacity to adapt is dynamic and influenced by economic and natural resources, social networks, entitlements, institutions and governance, human resources, and technology. But, high adaptive capacity does not necessarily translate into actions that reduce vulnerability. New planning processes were being implemented to attempt to overcome these barriers at local, regional and national levels in both developing and developed countries. AR4 noted the establishment of the National Adaptation Programmes of Action (NAPAs) and that some developed countries had established national adaptation policy frameworks. Other conclusions from the AR4 relating the implementation of adaptation policies and measures, barriers to adaptation and the economic costs of adaptation are summarized in Chapters 15, 16 and 17.

14.2. Adaptation Needs

Adaptation involves reducing risk and vulnerability, while building the capacity of nations, regions, cities, communities and individuals to cope with climate impacts as well as mobilizing that capacity by implementing

decisions and actions (Tompkins *et al.,* 2010). Vulnerability is the degree to which a system is "susceptible to, and unable to cope with, adverse effects of change" and is traditionally viewed as being comprised of three elements: exposure, sensitivity, and adaptive capacity (IPCC, 2007a, IPCC SREX, 2012). In other words, vulnerability is the stress faced by a system or individual, the extent to which the system will be affected, and the degree to which the system is able to cope with or respond to these stresses (Cutter, 1996; Cutter *et al*., 2003; O'Brien *et al*., 2004; Adger, 2006).

Adaptation requires that there is adequate information on risks and vulnerabilities to identify needs and appropriate adaptation options to mitigate risks and build capacity. This process of identifying needs is often rooted in a formal risk or vulnerability assessments. The risk-hazard framework, drawn primarily from risk and disaster management, focuses on the adverse effects that natural hazards and other climate impacts can have on a given location (Füssel and Klein, 2006). The emphasis in this approach is on the physical and biological aspects of impacts and adaptation (Burton *et al*., 2002). An alternative approach, which is rooted in a political economy perspective, examines the ways in which individuals, groups and communities are vulnerable to climate impacts. Here, the focus is on social vulnerability, with an emphasis on how structural factors such as institutions shape socioeconomic conditions that place human populations at risk (Blaikie *et al*., 1994; Adger and Kelly, 1999). Approaches to identifying needs and options are discussed further in the section 14.4 on assessments.

Assessments typically provide insight into the risks and vulnerabilities that will result from climate change in communities, cities, and nations and, in turn, offer a means to identify the presence of adaptation needs. Although needs are specific to particular groups and places, they tend to fit into a set of more general categories as summarized in 14-1. For instance, vulnerability at the national and sub-national levels is affected by geographic location, biophysical conditions, institutional and governance arrangements, and resource availability, including access to technology and economic stability.

[INSERT TABLE 14-1 HERE
Table 14-1: Categories and examples of adaptation needs.]

14.2.1. Institutional Needs

Institutions consist of formal and informal rules and norms the provide the enabling environment for implementing adaptation actions (Bryan et al., 2009; Chuku, 2009; Aakre and Rübbelke, 2010; Compston, 2010; Moser and Ekstrom, 2011b). These institutions provide the guides, incentives, or constraints that shape the distribution of climate risks, establish incentive structures that can promote adaptation, foster the development of adaptive capacity, and establish protocols for both making and acting on decisions (See 14.2.3.2 and Agrawal, 2010). At the international level, institutions and institutional actors enable and facilitate the distribution of adaptation resources and capacity support to developing countries. In many instances, international and national-level policies and programs can facilitate localized strategies through the creation of legal frameworks and the allocation of resources (Adger, 2001; Corfee-Morlot *et al*., 2009; Bulkeley and Betsill, 2005). Similarly, institutions, including political systems, policies, and politics at the national or sub-national levels can influence the vulnerability of certain sectors or can facilitate the success of adaptation actions within their jurisdictions (Chuku, 2009; Compston, 2010). For instance, drawing on case studies of water systems in the Middle East and North Africa, Sowers *et al*. (2011) maintain that the largely centralized systems of planning, taxation, and revenue distribution render governments more vulnerable since they are limited in their ability to adapt to climate change.

Local governments have the potential to directly enhance the adaptive capacity of vulnerable areas and populations by developing regulations including those related zoning, storm water management and building codes and attending to the needs of vulnerable populations through measures such as basic service provision and the promotion of equitable policies and plans (Adger *et al*., 2003; Nelson *et al*., 2007; Brooks *et al*., 2005). In the course of specific actions, local governments influence vulnerability and capacity by shaping access to resources and structuring individual and collective responses to climate impacts (Agrawal, 2010). There also are a number of ongoing political issues that shape the relationships local governments have to managing climate risks (Corfee-Morlot et al. 2011). For instance, short-term election cycles, when dealing with long-term issues can limit incentives to make

investments. Similarly, the proximity that authorities have to interest groups can sway their decisions toward other issues, while the drive to engage the public in planning and other activities can orient priorities in ways that do not support adaptation (Corfee-Morlot et al. 2011).

There are four critical institutional design issues that can be evaluated in order to understand institutional needs (Gupta *et al*., 2010; Agrawal**,** 2010). The first is the extent to which institutions are flexible. The uncertainty associated with climate change, presence of rapidly changing information and conditions, and emerging ideas on how best to foster adaptation requires continual evaluation, learning, and refinement (Gupta *et al*., 2010; Agrawal**,** 2010). Second is the extent to which adaptation is or has the potential to be integrated into short and long term policymaking, planning, and program development (Conway and Shipper, 2011). Third, is the potential for effective coordination, communication, and cooperation within and across levels of government and sectors (Schipper, 2009; Conway and Shipper, 2011; Agrawal, 2010). Finally, in order to promote adaptive capacity, it is important to identify the extent to which institutions are robust enough to attend to the needs of diverse stakeholders and foster their engagement in adaptation decisions and actions (Urwin and Jordan, 2008; Gupta *et al.,* 2010).

14.2.2. Social Needs

From a social perspective, vulnerability varies as a consequence of the capacity of groups and individuals to cope with the impacts of climate change. Among the key factors associated with vulnerability are gender, age, health, social status, ethnicity, and class (Adger et al., 2009; Smit et al., 2001). Climate change is expected to have a significant impact on the poor as a consequence of their lack of financial resources, poor quality of shelter, exposure to the elements, and limited provision of basic services, (Patz et al., 2008; Moser and Satterthwaite, 2010; Huq et al., 2007; Shikanga et al., 2009; Kovats and Akhtar, 2008; Revi, 2008; Tol et al., 2004; Gething et al., 2010; Rosenzweig et al., 2010). Due to limited financial resources and often compromised health and nutritional status, along with the sick and elderly, the poor are at increased risk from illness and death from climate-impacts such as increased pollution, higher indoor temperatures, exposure to toxins and pathogens from floods, and the emergence of new disease vectors (Kasperson and Kasperson, 2001;Haines et al., 2006; Costello et al., 2009; O'Neill and Ebi, 2009; Tonnang et al., 2010; Costello et al., 2011; Ebi, 2011; Harlan and Ruddell, 2011; Huang et al., 2011; McMichael and Lindgren, 2011; Semenza et al., 2012).

At the individual level, women, the elderly, those with health challenges and disabilities, low social, minority, and class status are among the least able to cope with threats from climate impacts (Adger *et al*., 2009; Smit *et al*., 2001). These individual factors also are often associated with and compounded by community-level conditions. Many poor and ethnic minorities live in substandard housing, lack access to basic services, have compromised health, and are at threat due to excessive densities, poor access roads, and inadequate drainage (Moser and Satterthwaite, 2010; Huq *et al*., 2007; Shikanga *et al*., 2009; Kovats and Akhtar, 2008; Revi, 2009; Baker, 2011). In rural areas, adaptation needs also are linked to the viability of agricultural activity (Bosello *et al*., 2009).

The causes and solutions of vulnerability take place at different social, geographic, and political scales (Ribot, 2010). Therefore, in order to identify critical needs of populations, and the underlying conditions giving rise to these needs, social assessments are best conducted across institutional domains and by spanning from the local to the national. Local assessments provide a means to identify existing vulnerabilities as well as policies, plans, and natural hazards contributing to these vulnerabilities. More specifically, at this level, social needs can be evaluated in terms of availability of natural, physical, human, political, and financial assets, stability of livelihood, and livelihood strategies (Moser, 2006; Heltberg *et al*., 2008). Alternatively, regional and national assessments can provide a basis for ascertaining institutional conditions associated with long-standing inequities and development paths that may need to be addressed in order to generate robust options.

14.2.3. Biophysical and Environmental Needs

Climate change is altering ecological systems, biodiversity conservation, and resources associated with ecosystem services (Convention on Biological Diversity, 2009; Mooney *et al.,* 2009; Hoegh-Guldberg, 2011). For instance,

González et al. (2010) used observed and modeled changes of global patterns of biome shifts under climate change and concluded that up to half of the terrestrial ecosystems were vulnerable often due to changes in stressors such as wildfire. They suggested that significant changes in management plans of natural resource management organisations. In addition to the responses of ecosystems to climatic change, a number of studies have identified impacts on ecosystem services, particularly the effects of climate change on agricultural productivity (Coles and Scott 2009), downstream industries and enterprises (Preston and Stafford Smith 2009), and freshwater ecosystems (Ormerod et al 2010).

Natural systems are important not only for their own sake, but also because they contribute to human welfare and prosperity in the face of a changing climate. For instance, coastal wetlands and coral reefs can help to protect against storm surges and rising sea levels (Hoegh-Guldberg, 2011) while the maintenance of wetlands and green spaces can control run-off and flooding associated with increases in precipitation (Jentsch and Beierkuhnlein, 2008; Mooney *et al*., 2009). Consequently, there is a need to protect these systems and resources within the changing climate, but many practices to improve and maintain ecosystem services are based on untested assumptions and limited information (Carpenter *et al.,* 2009). Tallis *et al*. (2008) found that only 16% of projects designed to deliver "win-win" goals of alleviating poverty and protecting biodiversity actually delivered both goals. Goldman et al. (2008) found that research projects that focused on delivering ecosystem services, rather than on biodiversity goals, attracted a wider set of funders and better-encompassed landscapes and the people within them.

14.2.4. Resource Needs

Successful implementation of adaptation actions depends on the availability of appropriate human capacity, information, access to technology and funding (Yohe and Tol, 2001; Adger, 2006; Eakin and Lemos, 2006; Smit and Wandel, 2006, World Bank, 2010). In some cases a supposed lack of information has been used as a rationale for inaction (Moser and Ekstrom, 2011a). To address this concern, the Nairobi Work Program, established at COP12 in 2006 with a goal of helping developing countries make better informed decisions based on sound scientific, technical and socio-economic data, has made repeated calls for better observation systems, information sharing, and modeling capacity (UNFCCC/SBSTA/2008/3). Developed and developing countries have acted upon this priority by establishing institutions to provide information services at national, regional, and global scales (UKCIP, 2011; NCCARF, 2012; CCCCC, 2011; WMO, 2011), and there is an ongoing need to promote information acquisition and dissemination (OECD, 2009).

Financial resources for adaptation have been slower to become available for adaptation than for mitigation in both developed and developing countries. Within developing countries only modest funding has been available for adaptation actions and much of this funding has been directed towards capacity building, standalone projects, or pilot programs. This not only has left financial needs, but has meant that there is less expertise in adaptation assessment and implementation, which is further confounded by the lack of clarity about the distinction between adaptation and more common sustainable development and/or poverty reduction planning (Cruce, 2008; McGray *et al*., 2007). Overall, at both international and national levels there is a need to develop financial instruments that are equitable in both their delivery of resources and in sharing the burden of supporting the instruments (Levina, 2007; World Development Report, 2010; Chapters 1,6 and 17). Also, financial mechanisms for disaster risk management are also inextricably linked with those for adaptation (Mechler *et al.,* 2010) and mechanisms for adaptation will have to balance immediate needs for essential development and disaster recovery with longer term goals directed to climate resiliency.

Financial transfers required in the future for climate change will likely approach those on current development expenditure (Peskett *et al*., 2009). Therefore, there is a related need to design delivery channels so that funding reaches the poor as they often are most vulnerable to the impacts of climate change. For example, for adaptation financing, working at the sub-national level will be important and mechanisms like microfinance merit a closer look (Agrawala and Carraro, 2010). Another important concern is that with new money being made available for climate change research, policy development, and practice, people may place too much emphasis on addressing climate change as an isolated priority to the detriment of other equally pressing social, economic, and environmental issues (Ziervogel and Taylor, 2008).

14.3. Adaptation Options

Identifying needs stemming from climate risks and vulnerabilities provides a foundation for selecting adaptation options. Over the years, a number of categories of options have been identified. These options include a wide range of actions that, as summarized in Table 14-2, can be organized into three general categories: structural/ concrete, institutional, and social (Carmin, et al, forthcoming 2013).

[INSERT TABLE 14-2 HERE
Table 14-2: Categories and examples of adaptation options.]

14.3.1. Structural / Concrete Options

This category highlight adaptation options that are discrete, with clear outcomes and outputs that are well defined in scope, space and time. They include structural and engineering options, the application of discrete technologies, the use of ecosystems and their services to serve adaptation needs, and the delivery of specific services at the national, regional and local levels. The notion of 'concrete' reflects the orientation of the Adaptation Fund, where the focus is on "discrete activities with a collective objective(s) and concrete outcomes and outputs that are more narrowly defined in scope, space, and time." (Adaptation Fund Board, undated).

Engineering is often at the forefront of delivering adaptation technologies and strategies (Dawson, 2007). Most engineering options are expert driven, capital-intensive, large-scale, and highly complex (McEvoy et al., 2006; Morecroft and Cowan, 2010; Sovacool, 2011). The most commonly cited engineered options include building seawalls, beach nourishment, upgrading existing infrastructures, and retrofitting buildings (Blanco et al., 2009; Koetse and Rietveld, 2012; Ranger and Garbett-Shiels, 2012).

Engineered adaptation options typically have two general limitations. First, they often must cope with uncertainties associated with projecting climate impacts arising from assumptions about future weather, population growth, and human behavior (Dawson, 2007; Furlow et al., 2011). Second, the longevity and cost of engineered infrastructure affect the feasibility at the outset (Koetse and Rietveld, 2012). They also are subject to consequences that were not anticipated. For example, after coastal Eastern England was devastated by the North Sea storm surge in 1953, hard engineered sea walls were put in place to protect the coast from erosion and inundation. However, the engineered alterations resulted in a new array of coastal instabilities, including disturbances in sediment supply and damages to coastal ecosystems (Adger et al., 2009; Turner et al., 2010). As a result, many have promoted a "phased capacity expansion" strategy, which allows engineered projects to undertake design modification as conditions or knowledge change and facilitate incremental project construction to ease the burden of upfront financing (Colombo and Byer, 2012).

In addition to engineering, structural adaptation measures in various sectors are being developed based on recent advances in technology and information processing. In food and agriculture sector, a suite of adaptation options have been developed and applied to reduce the adverse impacts of climate change on production (FAO, 2007; Stokes and Howden, 2010; Chapters 7 and 9). Technologies range from improved irrigation methods, plant breeding for greater drought tolerance, adjusting planting based on simulated yields (Semenov, 2006; Semenov, 2008; Bannayan and Hoogenboom, 2008), to transfers of traditional technologies such as floating gardens (Irfanullah *et al.,*2008).

With the rapid diffusion of Information and Communication Technologies (ICT), such as mobile phones and the internet, the unprecedented speed at which information is produced and shared is posing a new set of possibilities for communication. ICT provides opportunities for both top-down dissemination of relevant information such as weather forecasts, hazard warnings, market information, and advisory services. It can also generate essential information through bottom-up processes such as 'crowd sourcing' of useful information such as local flood levels, disease outbreaks, and the management of disaster responses. MacLean (2008) identifies three kinds of effects of the

rapid advances in ICT on adaptation and development in general: direct use for monitoring and measuring climate change as described above; as a medium for raising awareness; and as an enabler for a 'networked governance' based on networked open organisations.

Ecosystem-based adaptation (EBA), which is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (Convention on Biological Diversity, 2009), is becoming an integral approach to adaptation. Often, when faced with climate related threats, first consideration is given to technological and engineered approaches to adaptation. However, working with nature's capacity and pursing ecological options, such as coastal and wetland maintenance and restoration, to absorb or control the impact of climate change in urban and rural areas can be efficient and effective means of adapting (Huntjens *et al.*, 2010, Jones *et al.*, 2012). The use of mangroves and salt-marshes as a buffer against damage to coastal communities and infrastructure has been well researched and found to be effective both physically and financially in appropriate locations (Morris, 2007, Day *et al.*, 2007). They can also provide biodiversity co-benefits, support fish hatcheries and have mitigation value (Adger et al., 2005, Convention on Biological Diversity, 2009, Reid and Huq, 2005). Other EBA activities include integrative adaptive forest management (Bolte *et al.*, 2009; Guariguata, 2009; Reyer *et al.*, 2009), and the use of agro-ecosystems in farming systems (Tengö and Belfrage, 2004,), land and water protection and management, and direct species management (Mawdsley *et al.*, 2009).

Ecosystem-based approaches have a number of limitations. For instance, efforts at managing some ecosystems to provide particular services may be at the expense of other services. For example, to provide an effective wetland buffer for coastal protection may require emphasis on silt accumulation possibly at the expense of wildlife values and recreation (Convention on Biological Diversity, 2009, Dudley *et al.*, 2010). Similarly Goldstein et al (2012) found that in land-use decision making in Hawaii tradeoffs existed between carbon storage and water quality, and between environmental improvement and financial returns. A further consideration is that ecosystem-based approaches are often more difficult to implement and assess as they usually require cooperation across institutions, sectors and communities, and their benefits are also spread across a similarly wide set of stakeholders (Jones *et al.*, 2012). As yet it is difficult to demonstrate the effectiveness of this approach compared with others because, as with adaptation as a whole, there have been few formal assessments of the outcomes of ecosystem-based projects (Carpenter et al. 2009, Munroe et al. 2012).

Service provision consists of a diverse range of concrete measures. For instance, one measure to support to the most vulnerable populations is social safety nets. Efforts to address long-term and child malnutrition, which often result from loss of livelihood due to extreme weather events, particularly floods and droughts, (Hoddinott, *et al.*, 2008; Alderman, et al, 2009) offer an example of how safety nets can serve as a climate adaptation measure. While some studies have shown that food programs can be counterproductive to promoting livelihood or may not prevent malnutrition in non-emergency situations (e.g., Bhutta, *et al.*, 2008), programs designed to provide support via food programs, micro-finance or insurance at times of extreme events can provide an important bridge for vulnerable populations (Alderman *et al.*, 2010; Hoeppe and Gurenko, 2006; Hochrainer *et al.*, 2007; Meze-Hausken *et al.*, 2009).

Public health services also are important for tackling projected increases of disease incidences spurred on by climate change (Ebi and Burton, 2008; Garg et al., 2009; Edwards et al., 2011; Huang et al., 2011). For example, in countries where malaria is endemic, frequent adaptation options for addressing possible outbreaks include increasing use of mosquito nets, insecticides sprays, and controlling mosquito breeding by reclaiming land and filling drains(Garg et al., 2009). Governments at all levels are often also responsible for maintaining adequate access to services that are projected to be further stressed due to climate change (Laukkonen et al., 2009; Ernstson et al., 2010). Frequently cited options in this domain include, among others, clearing drainage systems to prevent floods, diversifying water supple services to account for changing water supplies (Kiparsky et al., 2012), and maintaining open public spaces dedicated for disaster recovery and other emergency purposes (Hamin and Gurran, 2009).

At the local level, infrastructure associated with the provision of basic services, such as water, sanitation, solid waste disposal, power, storm water and roadway management, and public transportation are integral to increasing adaptive capacity (Paavola, 2008; Hardoy and Pandiella, 2009; Bambrick et al., 2011; Barron et al., 2012). Housing services are particularly critical because new patterns in temperature and precipitation will alter the habitability and stability

of residences while increased frequency and intensity of natural disasters will place settlements and homes on both stable and unstable land at greater risk (Dodman and Satterthwaite, 2008). Although one option is to relocate people inhabiting vulnerable areas, some argue that in situ upgrading may be more cost effective, especially for addressing informal settlements in developing countries (Revi, 2008).

There are repeated calls for technology transfer to and sharing between developing countries in adaptation to match the programs associated with mitigation (UNFCCC, 2006). However, the circumstances are different. Unlike mitigation, where low-carbon technologies are often new and protected by patents held in developed countries, in adaptation the technologies are often familiar and applied elsewhere. For example, agricultural practices that are well known in a region some distance away may now be applicable but unfamiliar within a region of interest. There are some technologies that may become more important in adapting to climate change. Improved water transport and application through irrigation, or through water use efficiencies in industry all have particular technologies that need to be more widely available, as will desalination technologies. Revised building codes are another important opportunity to increase resilience to climate impacts, but again institutional issues such as enforcement are just as important.

14.3.2. Institutional Options

Numerous institutional measures can be used to foster adaptation. These range from financial instruments such as taxes, subsidies, and insurance arrangements to social policies and regulations (Hallegatte, 2009; Heltberg *et al.,* 2009; de Bruin *et al*., 2009). For instance, in the U.S., post-disaster funds for loss reduction are added to funds provided for disaster recovery and can be used to buy out properties that have experienced repetitive flood losses and to relocate residents to safer locations, to elevate structures, to assist communities with purchasing property and altering land-use patterns in flood-prone areas and undertaking other activities designed to lessen the impacts of future disasters (FEMA, 2010). Planning measures such as building codes and rezoning are institutional measures that can improve the safety of hazard-prone communities (Biderman et al., 2008; Bartlett et al., 2009). While zoning can be used to procure sites for low-income populations (Dodman and Satterthwaite, 2008; Biderman et al., 2008; Bartlett et al., 2009), if it increases property and housing values it also has the potential to exclude the poor from these areas.

A number of funding and financial issues are linked to institutions. At the international level, agreements and donors have a critical role to play in promoting and supporting the allocation and flow of financial resources (OECD, 2011). For instance, the Adaptation Fund, which is set up under the Kyoto Protocol and funded through a levy on most CDM projects, is of particular importance to developing countries as it is pioneering the direct access mechanism which allows countries to access funds without having to work through a multi-lateral development agency. The direct access mechanism highlights the role of institutions in building and maintaining capacity, not just in the technical aspects of adaptation assessment and project design, but also in financial management and due diligence (Brown *et al*., 2010).

Effective governance is important for the efficient operations of institutions. In general, governance rests on the promotion of democratic and participatory principles as well as on ensuring access to information, knowledge, and networks. The basic premise is that robust governance measures can promote adaptation by building adaptive capacity (Adger *et al*., 2009). This argument is reflected in assessment of river-basin planning in Brazil, where Engle and Lemos (2010) found that improving governance mechanisms appears to enhance adaptive capacity. However, they also note that this is not a simple relationship as tradeoffs exist between different aspects of governance that can make some approaches more or less appropriate for given contexts.

14.3.3. Social Options

The complexity of climate adaptation means that adaptation options are heavily influenced by forms of learning and knowledge sharing (Collins and Ison, 2009). Many have noted that education is a key indicator for how people select adaptation options (Chinowsky et al., 2011; Sovacool et al., 2012), while a lack of education is a constraint

that contributes to vulnerability (Paavola, 2008). For example, in a study of how farmers in the Nile Basin of Ethiopia select adaptation options, the researchers found a positive relationship between the education level of the household head and the adoption of improved technologies and adaptation to climate change (Deressa et al., 2009).

Awareness raising, extension, outreach, and other educational programs are important for disseminating knowledge about adaptation options (Aakre and Rübbelke, 2010; Birkmann and Teichman, 2010) as well as for helping to build social capital that is critical for social resilience (Adger, 2003; Krasny et al., 2010; Wolf et al., 2010). In this regard, education can be seen as a public good that promotes dialogue and networks (Boyd and Osbahr, 2010), and, therefore, allows the development of resilience at both the level of the individual learner and at the level of socio-ecological systems (Krasny et al., 2010).

Informational strategies are integral to adaptation. Early warning systems are critical to ensuring awareness of natural hazards and to promoting timely response, including evacuation. A number of approaches being employed around the world, including tone alert radio, emergency alert system, presentations and briefings, and reverse 911 (Pulwarty 2007; Van Aalst et al. 2008, Ferrara de Giner *et al*., 2011). Awareness raising through scenario development, computer modeling and role playing is effective in preparing both responsible authorities and the public (Box 14-1). As previously noted, ICT is facilitating rapid dissemination of information. However, low-tech measures such as brochures, public service announcements, and direct contact with local residents also are important to fostering awareness and response (National Research Council 2007).

_____ START BOX 14-1 HERE _____

Box 14-1. Scenarios and Public Education

Recently the U.S. Geological Survey's Multi-hazard Demonstration Project developed a hypothetical but realistic scenario for large winter storms called ARkStorm (the "AR" refers to atmospheric rivers) in California that was partially based on storms that struck California in 1861 and 1862, but that used state-of-the art modeling approaches. The scenario, which was developed by more than 100 scientists, engineers, and policy and insurance experts, included data on the meteorological aspects of the storms and on impacts such as flooding, landsides, damage to the built environment, and direct and indirect economic losses, as well as activities and expenditures required for recovery (see Porter et al. 2011 for details). ARkStorm was preceded by an earthquake scenario for Southern California, which was connected to a public education campaign and large-scale earthquake exercise known as the Great Southern California Shakeout. The same team is now developing a tsunami scenario for the ports of Los Angeles and Long Beach. All scenarios are accompanied by outreach to constituencies such as government officials and owners and managers of critical infrastructure systems, and include media collaborations, public service announcements, billboards, and other materials aimed at informing the public about hazards and their potential impacts.

_____ END BOX 14-1 HERE _____

Behavioral measures are among the suite of options that are integral to advancing climate adaptation. Government incentives can spark behavioral change. For example, to slow runoff into storm sewers and reduce flooding, a number of cities in the U.S. run "Disconnect your Downspout" programs. These programs will provide information to households and some offer rebates on supplies. Many poor and vulnerable communities have taken steps to adapt to changes in climate, particularly those in flood prone areas. For instance, some local communities in Manila are increasing the number of floors in homes and building makeshift bridges (Porio, 2011).

14.3.4. Selecting Adaptation Options

Selecting specific adaptation options can be challenging partly due to the rate, uncertainty, and cumulative impacts of climate change. However, such signals need to be interpreted and weighed against other cultural, economic, political or social signals that may encourage change. Indirect signals from regulators or customers may be a stronger signal to the agents responsible for adapting than the observed climate itself (Berkhout *et al*., 2006). Also,

rarely will adaptation options be designed to address climate risks or opportunities alone (IPCC, 2007b), instead actions will often be undertaken with other goals (such as profit or poverty reduction) in mind, while also achieving climate-related co-benefits. Gains in reduced vulnerability, enhanced resilience or greater welfare will often be co-benefits generated as a result of changes and innovations driven by other factors. Thus, rather than focusing on adaptation options addressing specific dimensions of climate change, more attention is being paid to mainstreaming climate change into wider government policy and private sector activities (Sietz *et al*., 2011).

A variety of systematic techniques have been developed for selecting options (e.g., DeBruin, 2009; Ogden and Innes 2007, 2009; Füssel 2009). Quantification and other systematic approaches to selecting options have many virtues. However, they also have limitations. For instance, most of these methodologies do not account for a range of critical factors such as leadership, institutions, resources, and barriers (Smith, et al., 2009). As an alternative, a variety of strategies have been recommended for selecting options. Strategies dominating the early adaptation literature emphasized maintaining the current system and minimizing costs while achieving some form of benefit. For instance, no-regrets, low-regrets strategies draw on measures that minimize costs and support existing or complementary goals. Win-win approaches are measures that both reduce climate risk and provide other social, economic or environmental benefits (Hallegatte, 2009). Adaptive management also is a strategy that is highlighted in the early adaptation literature. This approach, which draws on natural systems perspectives, places an emphasis on taking incremental action and then using the lessons learned to inform future actions. The intent is that by monitoring changes that take place and learning from the process, it will be possible to make better-informed decisions in the face of uncertainty (Holling 1978).

As ideas about adaptation have evolved, there has been a shift in orientation from traditional approaches that emphasize maintaining the status quo to more transformative strategies. This is best characterized by the integration of sustainable development into general conceptualizations of adaptation and from an emphasis on natural evolution to recognition of the centrality of human and policy intervention (IPCC SREX, 2012) and from engineering solutions to a balance of structural, institutional and social measures. Emerging trends in adaptation place an emphasis on the need for transformation, which has a distinct logic that differs from traditional strategies. Transformation refers to changes "in the fundamental attributes of a system, often based on altered paradigms, goals, or values. Transformations can occur in technological or biological systems, financial structures, and regulatory, legislative, or administrative regimes" (Glossary, AR5).

Whether the focus is on traditional or transformational strategies, a number of recommendations have been advanced for guiding the selection and sequencing of adaptation options. Given uncertainty, most approaches emphasize the need for basing decisions on multiple scenarios and for taking a long-term perspective. In terms of selecting specific options, the trend has remained consistent in noting the importance of accounting for resource availability and capacity limitations, and ensuring that overall approaches are (Table 14-3): flexible so they can be altered as conditions change, include safety margins so that more rapid rates of climate change are taken into account, can be implemented incrementally over time so that the financial burden is distributed, and find complementarities in structural/ concrete, institutional, and social measures (Hallegatte, 2009; Carmin and Dodman, forthcoming). In addition, the selection of measures must take into account both expert and local knowledge, equity, and stakeholder perceptions (Martens et al, 2009). Further, as discussed in detail in Chapter 16, an emphasis has been placed on identifying options that can be mainstreamed into sector initiatives and, in particular, with efforts in areas of climate mitigation, disaster risk reduction, and sustainable and economic development (Agrawala, 2005; Stern, 2006; Nelson et al., 2007; Agrawala and van Aalst, 2008; Ayers and Dodman, 2010; Willbanks and Kates, 2010; Willbanks et al. , 2003; Dowlatabadi, 2007; Klein, et al. , 2007; Swart and Raes, 2007; Larsen and Gunnarsson-Ostling, 2009).

[INSERT Table 14-3 HERE
Table 14-3: Considerations when selecting adaptation options.]

14.4. Actors and Roles in Adaptation

Climate adaptation requires the engagement of governmental, nongovernmental, private sector and community actors across levels and sectors. The identification of diverse needs, generation of appropriate options, and successful implementation of adaptation measures is predicated on diverse actors contributing their views, ideas, and expertise. This section outlines the roles of some of the main groups of actors and the challenges facing those groups in responding to climate change.

14.4.1. National and State Governments

Governments at all levels play important roles in advancing adaptation and in enhancing the adaptive capacity and resilience of diverse stakeholder groups. National governments are integral to advancing an adaptation agenda as they decide many of the funding priorities and tradeoffs, develop regulations, promote institutional structures, and provide policy direction to district, state, and local governments. In developing countries national governments are usually the contact point and initial recipient of international adaptation financing. State governments may have similar powers, the extent depending on the federal arrangements applicable to the country. In some countries, both developed and developing, state governments lead the national government in promoting and implementing adaptation (Mertz *et al*., 2009).

Drawing on an analysis of published articles, Berrang-Ford *et al*. (2011) found that upper levels of government, particularly national governments, tended to be more anticipatory, used institutional mechanisms such as laws and policies to foster adaptation. In some instances financial support was made available, particularly where adaptation was taking place at the national level. In addition, the engagement of national government actors can help mobilize political will, support the creation and maintenance of climate research institutions, establish horizontal networks that promote information sharing (Westerhoff *et al*., 2011) and, in some cases, facilitate the coordination of budgets and financing mechanisms (Alam *et al*., 2011; Kalame *et al*., 2011). Although there are general trends in the impact that national actors have on adaptation efforts, there also are differences between developed and developing countries. Among the key differences noted are that higher income countries more often include governmental engagement in planning and implementation, focus on non-resource-based sectors, pursue long-term planning processes that include activities such as building partnerships and research, and rely on institutional, governmental, and guideline-based protocols. Low and Middle-income countries tend to be engaged more in reactive adaptations based on community level mobilization often with weak engagement by governments (Berrang-Ford *et al*., 2011).

14.4.2. Local Governments

Local governments are integral and critical actors in advancing, or impeding, adaptation and in shaping the options identified and selected. As institutional actors, they influence the distribution of climate risks, mediate between levels of government as well as between social and political processes, and they establish incentive structures that affect both individual and collective action at all levels (Agrawal and Perrin, 2008). They are in a pivotal position to promote widespread support for adaptation initiatives, foster intergovernmental coordination, and facilitate implementation, both directly and through mainstreaming into ongoing planning and work activities (Carmin *et al*., 2012; Anguelovski and Carmin, 2011).

Despite the critical role they play, local governments, particularly those in developing countries, are faced with numerous challenges that limit their ability to identify needs and pursue adaptation options. Often, these governments must attend to backlogs of basic and critical services such as housing and water supply or focus their attention on addressing outmoded and outdated infrastructure. They also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Dodman *et al*., 2009; Hardoy and Romero Lankao, 2011). Also, they may encounter roadblocks both from within their communities as well as from other levels of government in setting priorities, obtaining and allocating resources, and engaging in coordinated action if their attention is focused on adaptation rather than more commonly accepted priorities.

Tompkins et al (2010) found from a survey of 300 adaptive[1] projects in the UK, that more than half were driven by concerns not directly related to climate change. Nevertheless, there are a number of indicators that demonstrate whether local government has institutionalized and mainstreamed adaptation. These include the presence of an identifiable champion from within government, climate change being an explicit issue in municipal plans, resources are dedicated to adaptation, and adaptation is incorporated into local political and administrative decision making (Roberts, 2008, 2010).

[FOOTNOTE 1: The definition of adaptation was extended to include any actions that affected the ability to cope with or adapt to climate change whether or not motivated by climate change.]

14.4.3. Local Civil Society and Nongovernmental Organizations

Civil society actors, including NGOs and community-based organizations (CBO), contribute to adaptation, both through dedicated initiatives as well as in the course of their ongoing work. They play a particular role in community-based adaptation (Menard, 2013). NGOs also have the potential to support government action, or highlight inaction, as well as to take independent action that facilitates adaptation across and beyond government programs. Cameroon, for example, has low adaptive capacity with limited ties within and across levels of government. While many government departments had limited awareness and were taking little to no action on climate change, Brown *et al*. (2010), found that NGOs and other civil society organizations contributed to government capacity. While many NGOs working at the local level focus on sustainable development rather than climate change, organizational representatives took advantage of the synergies in these two areas and were helping local residents prepare for climate impacts.

Governments initiate some programs, while others originate from NGOs and CBOs. In Quito, local NGOs receive funding from the government to train indigenous farmers to improve water resource management, particularly in the context of urban agriculture, diversify crops and privilege those that are native, and replant native tree species in hillside areas. The NGOs also work with indigenous communities, teaching them to monitor variations in rainfall and flows from local rivers and then sharing that data with municipal staff so that tracking of water levels is up-to-date (Carmin *et al*., 2012; Anguelovski and Carmin, 2011).

Civil society actors can play a role in hindering adaptation actions as well as alerting governments and the public to critical issues. These range from those who call into question the validity or urgency of climate change (Boykoff, 2008, McCright and Dunlap, 2013) to questioning the risks of particular approaches to adaptation, such as the use of gene technologies for developing new crop varieties (Hällström, 2008).

14.4.4. International Organizations and Institutions

International organizations and institutions include intergovernmental organizations, multilateral and bilateral agencies, multinational corporations, and nongovernmental organizations. These actors engage in a variety of activities that affect adaptation at the international, national, and local levels. Among the roles played by intergovernmental organizations is the formation of treaties and agreements and creation of international funding mechanisms. For instance, the Adaptation Fund and the Nairobi Work Programme, among others, are international institutions designed to facilitate adaptation at the national and regional levels (Ayers, 2009; Ayers and Huq, 2009; Flam and Skjaerseth, 2009; Hardee and Mutunga, 2009; Kalame *et al*., 2011; Lu, 2011). Multilateral and bilateral agencies typically focus on the provision of development assistance and the creation and implementation of capacity building programs. Through these efforts, agencies allocate funds, transmit information, and disseminate technology.

International NGOs, particularly international development, aid, and humanitarian organizations, have long histories of working on adaptation-related activities. Organizations such as CARE and Red Cross/Red Crescent work directly with communities to plan for water and sanitation as well as offer educational programs designed to provide information about climate risks (Suarez *et al*., 2008). Numerous development organizations work on issues related

to livelihood. Development initiatives not only have the potential to address poverty alleviation, but can reduce vulnerability by promoting adaptive capacity (Burton *et al*., 2002; Huq *et al*., 2003). As a number of studies show, while these activities may be oriented to promoting rural livelihoods in the context of environmental and development projects, they have co-benefits of building local capacity and promoting adaptive responses that enable communities to be better prepared to cope with climate impacts (Rojas Blanco, 2006; Pouliotte, 2009).

14.4.5. Local Communities

Many communities pursuing adaptation are engaging community-based, civil society, and nongovernmental organizations (NGOs) in planning and implementation. One approach that relies extensively on communities and community organizations is community-based adaptation (CBA). CBA is characterized by the engagement of local residents to identify measures that can reduce vulnerability while building local adaptation capacity. CBA can both engage as well as empower residents to plan for and take action to address the impacts of climate change (Reid *et al*., 2010; Ebi, 2008). It relies on participatory processes and not only considers hazard prone areas, issues in service delivery, and gaps in infrastructure, but often attends to local social and cultural norms as a means to take a holistic approach to reducing vulnerability (Ayers and Forsyth, 2009). The outputs of these processes have included numerous recommendations and plans of action, including the design and implementation of early warning systems, infrastructure development, and improvements in service delivery (Ensor and Berger, 2009; Douglas *et al*., 2008).

Communities have a long history of participating in vulnerability assessments and risk-mapping in the context of disaster risk reduction (Yamin *et al*., 2005; Larsen and Gunnarsson-Östling, 2009). Many of these ideas and methods have carried over into adaptation initiatives as a means to identify climate-related hazards and risks (Van Aalst *et al*., 2008). For instance, CBA has been adopted in the Philippines and Bangladesh to plan for flood reduction and disaster management (Ensor and Berger, 2009) as well as in cities such as Durban where local communities are engaged in climate risk assessments and adaptation planning (Carmin *et al*., 2012). These activities are designed to foster the transition from assessment to planning to implementation and, in the process, to sensitize communities to climate-related issues while promoting wide-spread adaptation action.

Community members also can contribute to local knowledge in support of government initiatives. For instance, in efforts to address climate adaptation and sustainable resource management needs, local residents from the southwest Yukon in Canada supported forest management plans by providing input on strategic benchmarks and design of appropriate harvest activities (Ogden and Innes, 2009). Governments have also used community engagement to ensure that local needs are met. For example, the Government of Fiji introduced a provision to delegate responsibility for surveying and assessing damage to the affected communities. The information that was collected was then used to inform the design of disaster response and recovery programs (Meheux *et al*., 2010).

14.4.6. Households

As adaptation is local in nature, households are the front line both in making decision about when and how to adapt and suffering the consequences increasing climate risks (Lansigan *et al*., 2007). The ability to respond to climate impacts is strongly related to household income, with wealthier households often being less exposed and having greater resources to draw upon, both to adapt and to recover from climate shocks (Masozera et al. 2007). Nevertheless, even they remain vulnerable weather shocks and the flow-on consequences, such as loss of power and/or water and livelihood disruption. Similarly cultural, social circumstances, gender and age affect the roles, empowerment and expectations of individual household members in both adaptation actions and in responses to climate impacts (Demetriades and Esplen, 2008). Poor rural households face some of the greatest difficulties from climate change. Climate related shocks threaten to overwhelm their current methods of income and consumption smoothing (Baez *et al*. 2013). For example many households protect consumption by sharing with and borrowing from relatives and friends, but such systems can fail as the frequency of damaging events increase (Deressa *et al*., 2009). There is also some evidence that poor farmers will seek to protect income by relying on low risk crops rather than higher value production systems (Azariadis and Stachurski, 2005). Frequent shocks can lead to a depletion of assets, both financial and human and eventually to a poverty trap. Evidence shows that school attendance suffers,

especially for girls, and early childhood malnutrition can impede development and capacity for the rest of life (Carter *et al*., 2007; World Bank 2010: Chpt 1). Stresses from climate events often adds to other pressures leading to rural to urban migration, which can increase the stresses in both locations. In many Arab countries men and boys migrate leading to further crowding and competition for jobs in the cities, while women are left to manage the farms often without rights of access to markets, rights to water *etc*. that were vested in the men (Verner, 2012: Chpts 1 and 7). This emphasizes the importance to households of social safety nets to avoid poverty traps (Morduch and Sharma, 2002; De Janvry *et al*. 2006; Hess *et al*., 2006).

14.4.7. Indigenous Peoples

Indigenous actors are in a particular position in relation to climate change. Many live in locations that are particularly exposed to climate change with resource-based livelihoods, and often with limited external resources and support to respond to a changing climate. As such they are often politically and economically marginalized and face substantial risks to livelihoods and culture from climate change (12.3). They are also the owners of knowledge systems that have served them through generations of climate variability, that provide local relevance, and that are attuned to their culture values and attitudes. (Nakashima, 2012). This knowledge is threatened through loss of context, concern about its continuing relevance and neglect (12.3.3). The respectful blending of this knowledge with that from scientific knowledge systems, which could inform both science and Indigenous Peoples, is still far from complete (Alexander *et al*., 2011, Thornton & Scheer, 2012). But progress is being made, including sharing of climate information and knowledge (Ziervogel et al. 2010) and in local information collection and monitoring (King et al., 2008; Anguelovski and Carmin, 2011). For instance, agro-pastoralists in Makueni District, Kenya are involved in monitoring, assessing, and adapting to the effects of drought through observing local weather and wildlife behavior signs (Speranza *et al*., 2010). Most progress is made in these exchanges if they are seen as a source of new insights for all those engaged rather than "contesting validities" (King and Goff, 2010).

14.4.8. Private Sector

The role of the private sector is fundamental in delivering adaptive changes. Most often, the focus falls on the role of the private financial sector in providing risk management options including insurance and finance for large projects (see Chapter 15). However, the delivery of adaptation actions ranges more widely and spans different types of private enterprise, from small farmers, to SMEs (Small to Medium Enterprises) to multinational companies. KPMG (2008) used published reports and interviews to identify the sectors where businesses face the greatest risks. In order of perceived importance the core risks were regulatory, physical, reputational and litigation risks. The sectors identified as most at risk included an expected cluster around oil & gas and aviation, and also a group less commonly perceived to be at risk, including health care, the financial sector, tourism and transport.

As shown in Figure 14-1, **t**here are three general ways in which the private sector can become involved in adaptation (Khattri, *et al.,* 2010). The first, internal risk management is critical to firms and enterprises protecting their own interests and ensuring continuity of supply and markets. The second form of involvement recognizes that business is a stakeholder and therefore needs to participate in public sector and civil society initiatives, such as, The New York City Panel on Climate Change, which consists of diverse stakeholders, including representatives from the private sector (Rosenzweig *et al*., 2011). Third, climate adaptation also provides a wide range of new opportunities to the business community. Even in developing countries Khattri *et al*., (2010) identified opportunities for working in the healthcare, waste and water management, sanitation, housing, energy, and information sectors through fostering cooperation across government departments and NGO and promoting public-private partnerships.

[INSERT FIGURE 14-1 HERE
Figure 14-1: A typology of private sector engagement in adaptation (Khattri *et al*., 2010).]

Despite broad-scale recognition of the need to adapt, such as the World Economic Forum's (2012) ranking of the failure to adapt as one of the highest global risks and on a par with terrorism, and despite some examples of private sector engagement in adaptation, most assessments conclude that action in each of the potential arenas has been

slow to emerge (Khattri *et al*., 2010, Agrawala *et al*., 2011). KPMG (2008) concluded that while companies are well used to managing business risk they are yet to integrate the long-term risks of climate change into these systems. Nor are they preparing to grasp the competitive advantages that will accrue to those taking early action. Most of the private sector appears to be unaware of the scale of the threat and opportunities for their businesses or are awaiting further guidance and action by governments. They have trouble in accessing and applying information on the extent of the threats and impacts from climate change and have yet to engage in the detailed cost benefit analysis of adaptive actions. Also, there are still questions of whether and how adaptation finance should be made available to the private sector in developing countries (Persson *et al*., 2009; IFC, 2010, Agrawala *et al*., 2011) although this is being piloted through the Pilot Program for Climate Resilience (World Bank, 2008; IFC and Asian Tiger Capital Partners, 2010). Private sector engagement and investment in adaptation is expected to make a substantial contribution to reducing climate risk, but the distribution of its investments will be selective and will be unlikely to match government and civil priorities (Atteridge, 2011).

14.5. Adaptation Assessments

14.5.1. Purpose of Assessments

Identifying adaptation needs requires an assessment of the factors that determine the nature of, and vulnerability to, climate risks (climate impacts and vulnerability assessments) and an assessment of adaptation options to mitigate risks (adaptation assessment).

Assessments help decision makers understand the impacts, vulnerability and adaptation options in a region, country, community or sector. They are often characterized into 'top-down' and 'bottom-up' assessments. Top-down assessments are used to measure the potential impacts of climate change using a scenario and modeling driven approach. Bottom-up assessments begin at the local scale, address socio-economic responses to climate, and tend to be location-specific (Dessai and Hulme, 2004). They are often used to determine the vulnerability of different groups to current and/or future climate change and their adaptation options, using stakeholder intervention and analyzing socio-economic conditions and livelihoods (UNFCCC, 2010). There are also policy-based assessments, which assess current policy and plans for their effectiveness under climate change within a risk-management framework (UNDP APF; UNDP, 2005). In practice assessments have become increasingly complex, often combining elements of top-down and bottom-up approaches (e.g., Dessai et al., 2005). Decision-makers use both in the policy process (Kates and Wilbanks, 2003; McKenzie Hedger et al., 2006).

14.5.2. Trends in Assessments

A variety of frameworks have been developed for the assessment of climate impacts, vulnerability and adaptation. 'Impacts-based' approaches focus primarily on the biophysical climate change impacts to which people and systems need to adapt. 'Adaptation-based' approaches examine the adaptive capacity and adaptation measures required to improve the resilience or robustness of a system exposed to climate change (Smit and Wandel, 2006). 'Vulnerability-based' approaches focus on the risks themselves by concentrating on the propensity to be harmed, then seeking to maximize potential benefits and minimize or reverse potential losses (Adger, 2006; IPCC, 2007). In practice these approaches are interrelated, especially with regard to adaptive capacity (O'Brien et al., 2006),

The 'standard approach' to assessment has been the climate scenario-driven impacts-based approach, which developed from the seven-step assessment framework of the IPCC (Carter et al., 1994; Parry and Carter, 1998):

1) Define problem (including study area and sectors to be examined)
2) Select method of problem assessment
3) Test methods/conduct sensitivity analyses
4) Select and apply climate change scenarios
5) Assess biophysical and socio-economic impacts
6) Assess autonomous adjustments
7) Evaluate adaptation strategies.

This approach dominated the assessment sections of the first three IPCC reports, and aims to evaluate the likely impacts of climate change under a given scenario and to assess the need for adaptation and/or mitigation to reduce any resulting vulnerability to climate risks (IPCC 2007). These frameworks are described as 'first generation' or 'type 1' assessment studies (Burton et al., 2002). The standard impact approach is often described as top-down because it combines scenarios downscaled from global climate models to the local scale with a sequence of analytical steps that begin with the climate system and move through biophysical impacts towards socio-economic assessment (IPCC, 2007).

The 'second generation' assessments (Burton et al., 2002) are characterized by vulnerability and adaptation assessments, which pay greater attention to information around vulnerability to inform decisions on adaptation. They focus on the participation of vulnerable groups in decision-making around adaptation options (LEG 2002).

Adaptation assessments continue to evolve, but most synthesis now include 'top-down' and 'bottom-up' approaches, and include the assessment of both biophysical climate change risks and the factors that make people vulnerable to those risks. There is a shift towards integrating community-based planning into national adaptation plans. The Government of Nepal proposes 'LAPA assessments' (Local Adaptation Plans of Action) that seek to integrate top-down and bottom-up models (Government of Nepal, 2011). There is also increasing attention to institutional capacity assessments and policy environments as key factors that can both drive vulnerability, and also determine the type and success of different adaptation options. The generic elements of adaptation and vulnerability assessment are reflected in the UKCIP guidelines presented in Figure 14-2.

[INSERT FIGURE 14-2 HERE
Figure 14-2: A generic framework for vulnerability and adaptation assessments (UKCIP, 2011).]

14.5.3. Issues and Tensions in the Use of Assessments

Adaptation and risk assessments give rise to various tensions, three of which are discussed in this section. The first is the 'adaptation paradox' which recognizes that climate change is a global problem, whilst vulnerability is locally experienced (Ayers, 2011). Top-down assessments of climate scenarios are deemed necessary in order to understand the climate change scenarios that render climate risk. However, the factors that make people vulnerable to climate risks are locally generated, so require locally driven bottom-up analysis. Bottom-up analysis tends to prioritise groups based on factors related to poverty and development that drive vulnerability. Top-down assessments tend to prioritise those most exposed to climate risks. Analysis in Nepal that assessed both under-development and climate change impacts showed that, at the household scale, there was a strong correlation between local measures of poverty and vulnerability to climate change (Ghimire et al. 2010). However, when indicators were aggregated at district scale, the correlation was weaker - even when the vulnerability index used included poverty as a proxy for adaptive capacity alongside climate hazard risk and exposure (Ghimire et al. 2010).

There are also tensions around ownership and participation. Assessments managed under global climate change governance structure of the UNFCCC are developed under an 'impacts-based' paradigm (Burton et al 2002). This impacts-based approach requires external scientific and technological expertise for defining climate change problems, and formulating technological adaptation solutions, based on specific knowledge of future climate conditions. Such assessments are necessarily 'top-down' because this expertise exists at the global and national level. At the local level, the capacity to adapt is based on the underlying securities that determine vulnerability to these impacts in the first place (Adger et al., 2003). Accessing this information requires 'bottom-up' and participatory assessments that engage local vulnerable people. These vulnerable groups and institutions do not have access to the climate impacts science necessary to fulfill the requirements of top-down impacts-based assessments. So there is a tension between enabling local participation under assessments driven by a global climate impacts remit.

The numerous assessments that have been carried out have led to a general awareness among decision makers and stakeholders of climate risks and adaptation needs and options. But this awareness is often not translated into the

implementation of even simple adaptation measures within ongoing activities or within risk management planning. To overcome this 'adaptation bottleneck' assessments may need to be linked more directly to particular decisions and the information tailored to facilitate the decision making process (Preston and Stafford Smith, 2009; Brown *et al.*, 2011). Specific techniques such as decision scaling, which seeks to understand which climate conditions would result in hazardous conditions of concern for particular stakeholder groups are a step in this direction (Moody and Brown, 2012; Brown *et al.*, 2012).

14.5.4. National Assessments

Under the Convention, all Parties are encouraged (Annex 1 countries are required) to report on their activities in relation to 'vulnerability assessment, climate change impacts and adaptation measures" (FCCC/CP/1999/7). Parties are encouraged to use the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994) and the UNEP Handbook on Methods for Climate Change Impacts Assessment and Adaptation Strategies (described above). Annex 1 countries are due to submit their 6th Communications by 2014 and most non-Annex I countries are due to have submitted at least one Communication and some their second. As such, National Communications have formed the first avenue for assessing and reporting on climate risk and vulnerability assessments at the national level.

National Adaptation Programmes of Action are designed as a vehicle for Least Developed Countries (LDCs) to communicate their most "urgent and immediate adaptation needs" to the UNFCCC for funding from the LDC Fund. "Urgent and immediate needs" are defined as those for which further delay in implementation would increase vulnerability or increase adaptation costs at a later stage (LEG, 2002:1). The approach adopted to vulnerability assessment under NAPAs vary. Although the guidelines allow for more participatory and 'bottom-up' mechanisms to be adopted, time and funding limitations has meant that often the NAPA process remains largely top-down, focused on impacts and only consulting the communities to verify this information (Ayers, 2001; Huq and Khan, 2006).

Under the Cancun Adaptation Framework (CAF), a process was established to enable least developed country Parties (LDCs) to formulate and implement National Adaptation Plans (NAPs). NAPs are intended to build on NAPAs but shift the focus towards identifying medium- and long-term adaptation needs and developing and implementing strategies and programmes to address those needs. Other developing country Parties are also invited to employ the modalities formulated to support the national adaptation plans in the elaboration of their planning efforts. Early guidelines (LDC Expert Group, 2002) propose a country-specific approach is adopted tailored to national circumstances, mixing top-down policy-first assessments with bottom-up approaches.

14.6. Measuring Adaptation

Adaptation has tended to lag behind mitigation efforts in both in research and in the climate negotiations. In part this because adaptation and development specialists, governments, NGOs and international agencies have found it difficult to clearly define and identify precisely what constitutes adaptation, how to track its implementation and effectiveness, and how to distinguish it from effective development (Burton *et al.*, 2002; Arnell, 2009; Doria, *et al.* 2009). A contributing reason is that adaptation has no common reference metrics in the same way that tonnes of greenhouse gases or radiative forcing values are for mitigation. This section seeks to explore the feasibility of finding metrics for measuring adaptation effectiveness.

The search for metrics[2] for adaptation will remain contentious with many alternatives competing for attention. This is inevitable as there are multiple purposes and viewpoints in approaching the measurement of adaptation (Hulme, 2009). Brooks et al (2011) asked 'what constitutes successful adaptation' and suggested that the criteria by which success might be assessed include, feasibility, efficacy/effectiveness, efficiency, acceptability/legitimacy, and equity (derived from Yohe and Tol, 2002; Adger, 2005; Stern, 2006), to which they added sustainability (see also Fankhauser and Burton, 2011). Also institutions, communities and individuals value things differently and many of those values cannot be captured in a comparable way by metrics (Adger and Barnett, 2009).

[FOOTNOTE 2: Here a 'metric' is defined as any type of measurement used to gauge some quantifiable component of performance; it is largely synonymous with the term 'indicator'. 'Metric' is used here to reduce confusion with the wider uses of the terms 'measure' and 'indicate'.]

At least three uses of measurements are relevant to adaptation each requiring different characteristics of its metrics. The first use seeks metrics to help determine the need for adaptation. These metrics usually focus on measuring vulnerability, but that term is not well defined as is discussed below. Further, even within this application often the goal is not to produce a score or rating for application but to elucidate information on the nature of vulnerability and to better identify adaptation options (Smit and Wandel, 2006). Hinkel (2010) identifies six uses that vulnerability indicators are sometimes expected to serve and concludes that they can truly serve only their core purpose; i.e. to identify vulnerable people, communities and regions. The second use of metrics relates to measuring and tracking the process of implementing adaptive actions, such as spending on coastal protection, the number of early warning plans implemented as part of a program, or the number of agricultural specialists with appropriate training in climate risks. Here the selection of appropriate metrics is usually less contentious but although there is disagreement as to how much they represent adaptation versus normal development. The third use relates to measuring the effectiveness of adaptation. This set is essential to help measure progress and provide feedback on the effectiveness of actions, but are among the most difficult to identify as adaption outcomes take time to become identifiable.

14.6.1. What Needs to be Measured?

The measurement of vulnerability is central to many adaptation metrics and initially it was approached from an impacts point of view. Here vulnerability is usually defined as a function of (i) exposure to specific hazards or stressors, (ii) sensitivity to their impacts and (iii) the target population's capacity to adapt (IPCC 2001, Chapter 17). This approach continues to be used as the basis of many assessments and adaptation prioritization efforts. Recently the emphasis has moved from better defining exposure and potential impacts to a better understanding of the factors that affect societies' sensitivity to those impacts and their capacity to adapt. This reflects the increasing recognition of the importance of considering social vulnerability alongside biophysical vulnerability. Various terms have been used to describe these different emphases including biophysical versus social vulnerability, outcome versus contextual vulnerability (Sections 14.2.1.1.1 and 14.2.1.1.2; Eakin and Luers, 2006; Füssel and Klein, 2006; Eriksen and Kelly, 2007; Füssel, 2007; Füssel, 2010) and scientific framing versus a human-security framing of vulnerability (O'Brien, 2006). O'Brien *et al.* (2007) argue that scientific and human-security frameworks affect the way we approach adaptation, with the scientific framework leading to building local and sectoral capacity to make changes rather than address the fundamental causes of vulnerability, or climate change itself, within their broader geopolitical and economic contexts.

Other questions also arise even within a given conceptual framework for considering vulnerability. A system of measurement is usually developed to allow comparisons between different places, social groups or sectors of activity, although experience repeatedly cautions us to be cautious in doing so (Schröter *et al.*, 2005). Also, a system's vulnerability is not static but can respond rapidly to changes in economic, social, political and institutional conditions over time (Smit and Wandel 2006; Smit and Pilifosova, 2003).

It has also been suggested that a framework based on the concept of resilience is more appropriate than a vulnerability framework in many contexts. For example, in a development context resilience "evokes positive and broad development goals (e.g., education, livelihood improvements, food security), includes multiple scales (temporal and spatial) and objectives, better captures the complex interactions between human societies and their environments, and emphasizes learning and feedbacks" (Moss *et al.*, to appear). A resilience approach also leads to more focus on interactions between social and biophysical systems (Nelson *et al.*, 2007). However, the concept of resilience has proven very difficult to apply in practice and is particularly resistant to attempts to establish commonly accepted sets of indicators. Some (e.g. Klein *et al.*, 2003) have suggested that resilience has become an umbrella concept that has not been able to support effectively planning or management.

Recently Brooks et al. (2011) have outlined a framework tracking adaptation that combines the establishment of upstream metrics to assess how well risks are being managed by institutions, and downstream metrics to track whether the interventions are reducing the vulnerability of affected groups. The upstream metrics would focus on assessments of institutional capacity, managerial performance, integration of climate risk management into planning processes and tracking and feedback processes. The downstream metrics would focus on measures to track development performance and changes in vulnerability. Attribution of these changes to particular interventions would be desirable, but not essential to track progress.

But understanding vulnerability does not necessarily translate to effective adaptation. Smit *et al*. (2001), Osman-Elasha *et al*. (2009) and others have suggested that the focus should be on increasing adaptive capacity within the context of the full range of biophysical and socio-economic stressors. However, as the scope of the metrics is widened to include aspects of development and sustainability they often become less suitable for other purposes such as helping to identify "the full and additional costs of adaptation" (McGray *et al*., 2007).

In deriving indices of vulnerability there are again two broadly different approaches. One is to deductively identify indicators that theoretically should be strongly related to vulnerability, while the other is inductive and uses observed data to seek correlations between indicators and observed consequences of vulnerability, such as the number of people killed or affected by climate related events in recent history. There is some commonality in identifying the desirable criteria for selecting indicators, which have been concisely summarized by Perch-Nielsen (2010) in Table 14-4.

[INSERT TABLE 14-4 HERE
Table 14-4: Set of criteria for selection of indicators.]

14.6.2. Established Metrics

14.6.2.1. Vulnerability Metrics

Numerous metrics continue to be prepared for a variety of purposes and at scales ranging from estimating the vulnerability of communities to comparing countries. Several reviews, including Moss (2001, to appear) Srinivarsan and Prabhakar (2008), and Prabhakar and Srinivarsan (2011), discuss both the design and effectiveness of many of the existing proposals for adaptation metrics.

Eriksen and Kelly (2007) found strong divergence among five 'indices' for comparing national vulnerability published over the period 1995 to 2003. (Namely the Dimensions of vulnerability of Downing *et al*., 1995; the Index of Human Insecurity (IHI) of Lonergan *et al*. 1999; the Vulnerability-resilience indicators of Moss *et al*., 2001; the Environmental Sustainability Index of the World Economic Forum, 2002; and the Country-level risk measures, Brooks and Adger 2003.) Between them, 29 indicators were used with only five indicators appearing in more than one study. They were able to compare the 20 countries ranked as most vulnerable from three of the studies and found little overlap with only five countries ranked in the top 20 in more than one study. However, it must be noted that the indices were developed at different times and for different purposes. They concluded that the indices focused on measuring a snapshot of aggregate conditions rather than on delivering guidance on societal processes that can be targeted to reduce vulnerability.

There are a series of disaster related indices designed to assess relative risks across countries and regions, and to provide benchmarks on which to assess progress (UNDP Disaster Risk Index, 2004; Hotspots Index of Dilley *et al*., 2005; the Americas Index of Cardona, 2005; and an index for South Asia of Moench *et al*., 2009). Again there has been little effort to further analyse, validate or compare these indices.

14.6.2.2. Metrics and Resource Allocation

Vulnerability indices have usually been designed to better understand the drivers of vulnerability or to compare countries, regions, communities etc. in terms of the risks they face from climate change and their capacity to deal with them. This is not necessarily the same as designing an allocation index or rule to be used to allocate limited resources equitably and efficiently among entities (countries, regions or other administrative groups, or different proponents of adaptation). For allocation we might expect that vulnerability and coping/adaptive capacity would remain a core consideration, but so also should the ability of the recipients to absorb the funding and implement policies and projects to actually achieve the projected benefits (UNFCCC, 2007; Wheeler, 2011).

One of the longest running and prominent use of metrics in funding is the World Bank's process of allocating IDA concessional funds to developing countries which faces many issues analogous to the same process for adaptation. The World Bank uses the Country Policy and Institutional Assessment (CPIA) based on 16 criteria to estimate the extent to which a country's policy and institutional framework supports sustainable growth and poverty reduction, and consequently the effective use of development assistance. These criteria are the main components used to calculate a Country Performance Rating, which in turn is a major component, along with population and recent performance measures, in calculating allocations to the poorest developing countries with long-term, no interest (IDA) loans. The CPIA and the ultimate IDA allocation formulae are controversial, much debated (Alexander 2010), often fine-tuned (IEG, 2009) but still commonly used as a reference point for this type of procedure (GTZ, 2008).

An explicit example of the use, and non-use, of adaptation metrics was in establishment of the Pilot Program for Climate Resilience (PPCR). The governing body made up of contributors, recipients and other stakeholders set up an independent expert group to make recommendations as to which countries might be included as pilots within the c. USD1billion program (Climate Investment Funds, 2009). The expert group refrained from using a simple index, but instead country selection was done across 9 regions and each based on a suite of indices appropriate for the region and on expert judgment. It is interesting to note that on moving to the next step of deciding on allocation of financial resources to the selected pilot countries the governing body of the PPCR chose not to use an approach based on indicators, but to provide guidance to the countries of the possible range of funding and to base allocations on the quality of the proposals bought forward (Climate Investment Funds, 2009). Similarly, none of the other governing bodies of international adaptation funding mechanisms (e.g. the GEF, the Adaptation Fund) has chosen to use a defined set of metrics within their decision-making.

Wheeler (2011) has developed an index of vulnerability based on weather related disasters, sea-level rise and agricultural productivity. The index can be adjusted according to user preferences to develop allocation formulas based only on biophysical vulnerability, further adjusted for economic development and governance, and finally for project costs and probability of success. Klein and Möhner (2011) have discussed the options for the Green Climate Fund based on experience to date and conclude that science cannot be relied upon for a single objective ranking of vulnerability.

14.6.2.3. Metrics for Monitoring and Evaluation

The IPCC's *Fourth Assessment Report* provided little discussion of the role of evaluation and monitoring of adaptation responses as a component of building adaptive capacity (Adger *et al*., 2007). Preston *et al*. (2011) identify three specific roles of evaluation: a) ensuring reduction in societal and ecological vulnerability; b) facilitating learning and adaptive management; and c) providing accountability for adaptation investments (see also GIZ 2011). A central challenge in developing robust monitoring and evaluation frameworks for adaptation is the existence of multiple, valid points-of-view that can be used to evaluate adaptation (Gagnon-Lebrun and Agrawala, 2006; Perkins *et al*., 2007; Füssel, 2008; Smith *et al*., 2009; Ford *et al*., 2011; Preston *et al*., 2011). This challenges the selection of appropriate metrics for the monitoring and evaluation of adaptation and its contribution to vulnerability reduction (Burton and May, 2004; Gagnon-Lebrun and Agrawala, 2007; Hedger *et al*., 2008; IGES, 2008; Ford *et al*., 2011).

One of the central unresolved tensions in progressing evaluation is the relative merit of targeting adaptation processes versus outcomes. Preston *et al*. (2011) suggest the evaluation of adaptation processes may be a more robust approach to evaluation, due to the difficulties in attributing future outcomes to adaptation strategies and the long-time lags that may be needed to assess the performance of a particular strategy (Berkhout, 2005; Dovers and Hezri, 2010; Ford *et al*., 2011). The OECD analyzed the monitoring and evaluation processes across 106 adaptation projects across six development agencies and found that Results Based Management and Logical Framework approaches dominated as they do in normal development projects (Lamhauge *et al*., 2011). They also drew attention to the need for appropriate baselines and complimentary sets of indicators that track not just process and implementation, but also the extent to which targeted changes are occurring. Monitoring programs themselves will need careful design to ensure that they remain in place over the long timeframes needed for the outcomes to be identified; that they contain incentives for beneficiaries to comply with conditions and that compliance itself does not impose undue burdens.

A number of national and international organizations have guides to monitoring and evaluating adaptation activities (McKenzie Hedger *et al*., 2008; UNDP, 2008; WRI, 2009; World Bank, 2010; GIZ, 2011). These guides tend to focus on the wider framework of identifying and managing adaptation-related activities and within that the criteria for the selection of metrics for monitoring and evaluating those activities. These issues are dealt with in Chapters 15 and 16.

14.6.3. Validation of Metrics

The practice of developing and applying metrics in adaptation has been subject much scrutiny. Eakin and Luers (2006) express serious concerns about national-scale vulnerability assessments ranging from the quality of the available data, the selection and creation of indicators, the assumptions used in weighting of variables and the mathematics of aggregation. Downing (to appear) has made a similar critique. Nevertheless indices will continue to be used and the challenge is to identify and maintain basic standards of best practice.

One of the most comprehensive attempts to validate a system for measuring important components of adaptation is that of Brooks, *et al*., 2004. They used the probability of national climate related mortality from the CRED data-base as a proxy for risk and selected a set of 46 social, governance, economic and biophysical measures as indicators of social vulnerability. They found that 11 were effective indicators of mortality rates and these were confirmed as useful by a small focus group of seven adaptation experts. These experts also ranked the variables in terms of their perception of their usefulness leading to a total of 12 different rankings to which was added an equal ranked set to give 13 measures of vulnerability. Countries were then scored against these 13 rankings and the number of times a country appeared in the top quintile of countries in a particular ranking was used as an indicator of its overall vulnerability.

Perch-Nielsen (2010) developed an index to estimate the vulnerability of beach tourism using a systematic approach by establishing a framework to identify the types of measures needed and a systematic approach to identify measures that covered the range of countries and time scales. The derivation of the index from the separate measures was also subjected to robustness (sensitivity) testing to determine the most appropriate methods of scaling and combining the measures.

14.6.4. Assessment of Existing and Proposed Metrics for Adaptation

Srinivarsan and Prabhakar (2008) conducted a wide-ranging stakeholder survey to assess the attitudes to, and requirements for, indicators of adaptation. Stakeholders agreed that no single metric can capture the multiple dimensions of adaptation and that refinements of methodologies (e.g. rationale for index selection, aggregation methods, and data checking) are badly needed. Preston *et al*. (2009) has suggest that, rather than seeking particular metrics, researchers should focus on developing rigorous processes for selecting metrics that can be applied in a range of contexts.

But metrics for adaptation remain a necessity. Their derivation challenges the adaptation community to clarify its goals, conceptual models, definitions and applications. But as both theory and practice has shown indicators alone are not sufficient to guide decisions on which adaptation actions to take, on how to modify sustainable development activities, or on resource allocation. Downing (2003) noted that the climate change community was far from adopting common standards, paradigms or analytic language. This still appears to be true, making the search for commonly accepted metrics, even within well-specified contexts, a challenging task.

14.7. Addressing Maladaptation

The adaptation literature is replete with advice to avoid maladaptation, but it is less clear precisely what is included as "maladaptation". In a general sense it refers to cases where actions to improve the welfare of target groups may result in adverse climate-related outcomes or increased vulnerability to climate change to either the target community at a later date, or more immediately to other communities. For example, the construction of well engineering of roads to withstand current and future climate extremes may foster new settlement into areas highly exposed to the impacts of future climates; or increased water harvesting upstream to cope with erratic rainfall may harm and reduce the opportunities for communities downstream to manage their own risks. The AR5 defines maladaptive actions as "those that may lead to increased risk of adverse climate-related outcomes or increased vulnerability to climate change now or in the future". Actions that are potentially maladaptive need not be inadvertent as in the IPCC AR3 and AR4 definition, nor "taken ostensibly to avoid or reduce vulnerability to climate change" (Barnett and O'Neill 2010) as the actions may be assessed as appropriate given the full range of climate and non-climate considerations and pressures that apply. There should be clarity as to what is maladaptive action, or lack of action, lest the avoidance of maladaptation becomes a barrier to effective implementation of adaptation. In the road example above, the immediate and multiple benefits to the community of a reliable road system (including as evacuation route in floods etc.) might be judged as outweighing the longer-term risk of inappropriate settlement patterns. The true maladaptation in this case would be the failure to implement appropriate incentives or regulations to avoid settlement in the highly exposed areas.

The complexity of the concept and terminology is further demonstrated by the recent introduction by Thomsen et al. (2012) of the term "manipulation" that has some similarities to the concept of maladaptation. They see adaptation as "behaviors that are respectful of the intrinsic integrity of social-ecological systems and change is directed toward internal or self-regulating modification", whereas manipulation consists of behaviors that disregard this integrity and seek to override self-regulation. Their example is the management of Noosa beach in northern Australia. This coastline is characterized by cycles of erosion and depletion of beach sands, but rather than enhance the self-regulatory processes and adapting by managed retreat and expansion according to the cycle, management has sought to maintain a static beach profile through hard constructions and beach nourishment. This may seem synonymous with maladaptation, but they differ because with manipulation there is a decision not to adapt. Niemeyer et al. (2005) also describe the state of individual beliefs about climate change that might lead to adaptive, maladaptive or non-adaptive behaviors, while Eriksen et al. (2011) and Brown (2011) discuss avoiding outcomes that are essentially maladaptive under a title of 'sustainable adaptation'.

14.7.1. Causes of Maladaptation

Maladaptation arises in many forms but several broad causes can be identified. One is development policies and measures that deliver short-term benefits or economic gains but lead to greater vulnerability in the medium to long-term, such as the construction of 'hard' infrastructure that may reduce flexibility and the range of future adaptation options (Adger *et al*., 2003; Eriksen and Kelly, 2007, OECD**,** 2009), or the failure to encompass the full range of risks, such as the effects of increasing storm surge in the design of a coastal defense system (UNFCC, 2007d). Adaptation efforts aimed at armoring the coastline may result in coastal erosion elsewhere while building levees along a flood-prone area might encourage unwanted development within that area often accentuated by a false sense of safety (Grothmann and Patt, 2005; Repetto, 2009; National Research Council, 2007) and the levees may increase damage when they fail as in Bangladesh in 1999 and New Orleans in 2003 (IDS, 2006). Similarly, agricultural policies that promote the growing of a high yielding crop varieties through subsidies with the objective of boosting

production and increasing revenues may reduce agro-biodiversity and increase exposure and vulnerability of mono-crops to climate change and finally undermine the adaptive capacity of farmers (World Bank, 2010).

Another cause is the failure to account for multiple interactions and feedbacks between systems and sectors leading to inadequate or inaccurate information for developing adaptive responses and strategies that are maladaptive (Scheraga *et al*. 2003, Satterthwaite *et al*, 2009, Pittock, 2011). An assessment of the downstream impacts of upstream rainwater harvesting in a semi-arid basin in Southern India showed that, once the full range of externalities were accounted for, the net benefits were insufficient to pay back investment costs (Bouma *et al*., 2011). Similarly, the conversion of coastal mangroves into shrimp farms that may increase economic productivity, but also lead to increased vulnerability to flooding and storm surges (Klein, 2010).

14.7.2. Screening for Maladaptation

Five dimensions of maladaptation were identified by Barnett and O'Neill (2010) including actions that, relative to alternatives: (i) increase emissions of greenhouse gases; (ii) disproportionately burden the most vulnerable; (iii) have high opportunity costs; (iv) reduce incentives and capacity to adapt; and (v) set paths that limit future choices. These dimensions are useful pointers to the potential for maladaptation but their application tends to be subjective. The first assumes a fungibility between mitigation and vulnerability; the second turns on the interpretation of "disproportionately", and the third on "high" and on how opportunity costs are compared with current benefits. The dimensions were used by Barnett & O'Neill (2010) to describe maladaptive potential of the Wonthaggi desalinization plant to improve water supply to Melbourne, Australia. They conclude the plant will (i) increase GHG emissions (unless the promised wind power energy source is completed), (ii) lead to higher water costs that will disproportionally affect the poorer households; (iii) divert money and attention from more cost effective recycling and rainwater harvesting, (iv) reduce incentives to adapt through water conservation approaches, and (v) as a large sunk cost has locked out other options. The plant also affected significant cultural sites of the Bunurong Aboriginal community (Lee and Chung, 2007).

14.7.3. Experiences with Maladaptation

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one sector could increase vulnerability of another sector or increase the vulnerability of a group to future climate change. An example is the situation experienced by subsistence and smallholder agriculturalists in Palca, Bolivia who, in the face of stressors relating to land access, small holdings etc., moved away from their long established practices of diversification of crop varieties and planting locations to more intensive farming practices and cash cropping. They are now seeing evidence of climate change and the new practices make them more vulnerable to these changes leading to a risk of insufficient adaptation and maladaptation (McDowell and Hess, 2012). But there can also be tensions between development goals and climate change goals, where people may be aware of a climate related risk but are willing to take that risk (or they may have limited choice) given their current circumstances (IPCC SREX 2012, section 4.2.2).

Some studies warn against the simplistic use of maladaptation to communicate the state of high exposure to risks resulting from certain type of livelihoods. For example, the periodic movement of the nomadic pastoralists following the grass and water is a traditional and effective way of dealing with climate variability (Agrawal and Perrin, 2008), but is increasingly being described by some as maladaptive. More focused studies such as Young et al. (2009) put the breakdown of traditional pastoralism in the Sudan into the wider social and political context that led to restrictions on movement, asset stripping and escalating violence and undermined by policies not conducive to mobility.

14.7.4. Relationship between the Adaptation Deficit and Maladaptation

Adaptation deficit is a related but different concept from maladaptation and is defined as the gap between the current state of a system and a state that minimizes adverse impacts from existing climate conditions and variability. It can also be described as the inadequate adaptation to the current climate conditions (Burton *et al*., 2002; Burton, 2004; Parry, 2009; Chapter 17.xxx). The deficit may arise from past inaction, the mismanagement and depletion of natural resources, or maladaptive decisions in the past. The adaptation deficit may also result from a low level of development and the consequential reduced capacity to cope with climate variability. Thus, the adaptation deficit may be considered part of a larger 'development deficit' (World Bank, 2010). In the process of building future adaptive capacity it is important to reduce the current adaptation deficit along with designing effective risk management and climate change adaptation measures (Hallegatte *et al*., 2011).

14.8. Research Gaps and Data Gaps

[To be developed along with other chapters in next draft – a single section in a chosen chapter]

Frequently Asked Questions

FAQ 14.1: Are there different definitions of adaptation, and if so why, and are they important?

The most commonly used definitions of adaptation remain based on the IPCC AR3 (2001) definition ("adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities"), but with some important elaborations being introduced. The IPCC SREX (2012) and AR5 have modified the definition to deal separately with human and natural systems and included an element of purposefulness in human adaptation actions (i.e. "which seeks to moderate harm ...")[3]. Earlier IPCC Reports also defined the terms 'anticipatory', 'autonomous' and 'planned' adaptation, but the use of these terms in the IPCC and the literature has been inconsistent. The focus now is more on identifying terms in use in the UNFCCC negotiations such as 'concrete adaptation' measures [14.3.1] and incremental versus transformative adaptation [14.3.4].

Similarly, questions arise as to whether adaptation to climate change can, or should, be distinguished from normal development actions [15.x]. Adaptation and development are inextricably linked. Development that brings improvements in livelihoods, greater access to resources and more resilience to the wide variety of volatilities faced by household and communities, will usually also achieve adaptive outcomes. However, pursuing development priorities without looking ahead to a world with a changed climate could undermine development efforts either by failing to adjust to the possibility of changed climate [14.2; 15.x] or through actions that cut off options to deal with changed climates, i.e. maladaptation [14.6]. Increasing focus on the costs of adaptation and on evaluating adaptation practices has led to more attention to what constitutes *successful* adaptation. Some definitions of success emphasize reducing risks to a predetermined level while other focus on achieving predetermined levels of social and or economic well being [17.x].

[FOOTNOTE 3: IPCC AR5 definition of adaptation is "In human systems, the process of adjustment to actual or expected climate and its effects, which seeks to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate."]

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Table 14-1: Categories and examples of adaptation needs.

Categories	Examples of needs
Institutional	Inadequate laws, policies, incentives, plans, and procedures, as well as a lack of informal norms, to promote and support adaptation.
Social	Public and private needs arising from social conditions, such as poverty, health status, ethnicity, and age that increase vulnerability and risks.
Biophysical and Environmental	Need for actors and actions to maintain or improve ecosystem health, ecological productivity, and agricultural productivity while also addressing increasing the vulnerabilities of peoples who depend on these ecosystem services.
Resource	Insufficient financial, human, technological, informational, and social resources required for planning and implementing adaptation.

Table 14-2: Categories and examples of adaptation options.

Category	Examples of Options
Structural/Concrete	
Engineered	Sea wall; Water storage; Improved drainage; Beach nourishment; Flood shelters
Technological	New crop & animal varieties; Efficient irrigation and water use; Hazard mapping and monitoring; Early warning systems; Home insulation
Ecosystem-based	Wetland re-establishment; Re-establish floodplains; Bushfire fuel-reduction actions
Services	Social safety nets; Food banks; Vaccination programs, Municipal services
Institutional	
Economic	Financial incentives; Insurance & other risk spreading
Laws and Regulations	Land zoning laws; Building standards; Easements
Government Policies and Programs	National & local adaptation plans; Urban upgrading programs; Municipal water conservation programs; Disaster planning and preparedness
Social	
Educational	Awareness raising; Extension services
Informational	Hazard mapping and monitoring; Early warning; Community support groups
Behavioral	Household preparation; Evacuation planning; Retreat and migration; Water conservation; Storm drain clearance.

Based on: Carmin et al, 2013.

Table 14-3: Considerations when selecting adaptation options.

- Minimizing cost
- Maximizing benefit
- Mainstreaming with goals, programs, activities
- Flexibility
- Safety margins
- Resource availability
- Potential for incremental implementation
- Equity
- Stakeholder input

Table14-4: Set of criteria for selection of indicators.

	Criterion	Explanation
Validity	Well-founded	Based on a tested theoretical framework
	Accurate	Really measuring what it should
	Non-ambiguous	Agreement on the direction of influence between the indicator and vulnerability
Use	Comprehensible	Relatively easy for users to understand
Type	Relevant	Applicable to many geographic and economic conditions
	Responsive to changes	Can be influenced by action
	High information content	No yes/no indicators, and preferably actual performance data instead of model-based data
Data	Available	Data that is publicly and easily available
	Homogenous and periodical data	Data that is collected homogeneously, making it suitable for international comparisons

From Perch-Nielsen, 2010 – based on Aitkins et al., 1998; Esty et al., 2006 Kaly et al., 2003 and OECD, 2002.

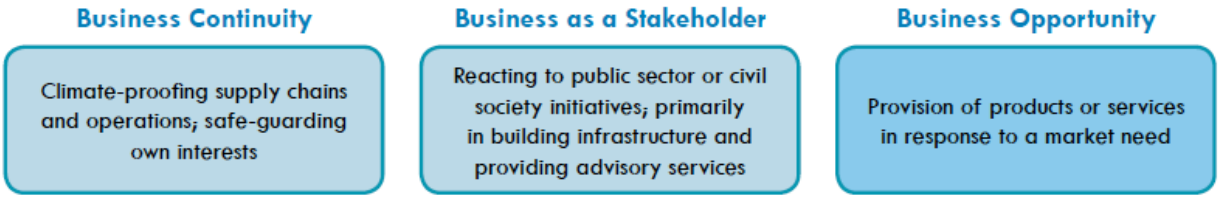

Figure 14-1: A typology of private sector engagement in adaptation (Khattri et al., 2010).

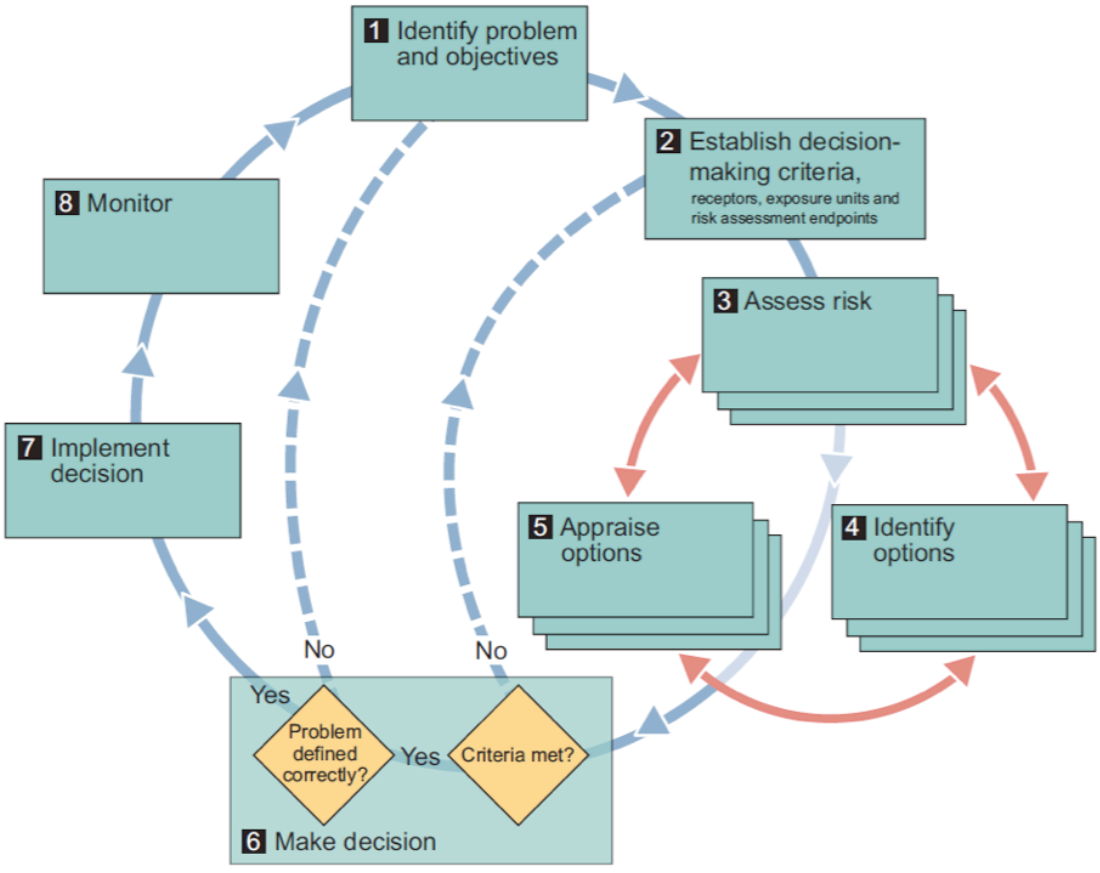

Figure 14-2: A generic framework for vulnerability and adaptation assessments (UKCIP, 2011).

Chapter 15. Adaptation Planning and Implementation

Coordinating Lead Authors
Nobuo Mimura (Japan), Roger Pulwarty (USA)

Lead Authors
Do Minh Duc (Vietnam), Ibrahim Elshinnawy (Egypt), Margaret Hiza Redsteer (USA), He-Qing Huang (China), Johnson Ndi Nkem (Cameroon), Roberto A. Sanchez Rodriguez (Mexico)

Review Editors
Richard Moss (USA), Walter Vergara (Interamerican Development Bank)

Volunteer Chapter Scientists
Lisa S. Darby (USA), Sadahisa Kato (Japan)

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Cross-Chapter Box
CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

References

Executive Summary

Adaptation planning is transitioning from a phase of awareness and promotion to the construction of concrete responses in societies (high agreement, robust evidence). [15.2] The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised the importance of adaptation to climate change. National-level plans and adaptation strategies for developed countries are dominated in the literature than for developing countries; whereas, more implementation cases are documented at the local level in developing countries. Attention to climate change impacts and disaster risk management, which are key elements of adaptation planning, appear to have a more prominent role in developed countries. In contrast, there is a trend to link adaptation planning to development needs and stresses in developing countries. This has had implications in terms of the resources and institutional needs to support adaptation planning and its implementation in developed and developing countries. Although the transition in adaptation planning represents a positive trend compared to the previous IPCC reports, it is not clear yet whether the observed adjustments and changes to perceived climate risks represent evidence of a societal shift towards a well-adapting society.

The social dimensions of adaptation have attracted more attention, including the relationship between adaptation, and development and disaster risk management (high agreement, robust evidence). [15.2.1] Climate change adaptation (CCA) takes place as a response to multiple stimuli, which highlights the need of connecting CCA with the development and disaster risk management (DRM). The importance of CCA is influenced by how the issue is framed, and to the extent that it is viewed as a public safety issue or a development issue, it may have greater resonance within national and local policies. Therefore, the linkages between adaptation, development

and DRM need to be more explicit targeting co-benefits among them. As knowledge of impacts and vulnerabilities solely is not sufficient to lead to the most effective and efficient adaptation policy decisions, due to the context specificity of adaptation, it is needed to build operational approaches of adaptation planning by recognizing the structural socio-economic conditions and agency of individuals and communities in low and middle-income countries.

The national level plays a key role in adaptation planning and implementation, while adaptation responses have diverse processes and outcomes at national, subnational and local levels (high agreement, high evidence). [15.2.2] National governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy frameworks, creating legal frameworks, actions to protect vulnerable groups, and financial support to other levels of government. Despite the embryonic state of the adaptation process, an assessment of the characteristics and effectiveness of the coordinating role of national adaptation strategies and plans is an urgent pending task. The number of adaptation responses has increased at the local level in developed and developing countries. However, there is a common trend that local governments are hindered by the absence of applicable guides to adaptation decision-making. Local councils and planners are often confronted by the complexity of adaptation, and even when information is available, they are left with a portfolio of options to prepare for future climatic changes and the potential unanticipated consequences of their decisions. Therefore, linkages with national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders are important.

Adaptation efforts in some developing countries provide a 'win-win' adaptation strategy that strengthens resilience to climate change while improving economic stability and environmental quality. (high agreement, medium evidence). [15.3.1] Climate change adaptation efforts also improve ecosystem resilience by implementing sustainable forestry quotas, expanding floodplain setbacks, implementing coastal afforestation, coral reef propagation, restoring degraded lands, maintaining healthy vegetation on slopes, incentivizing development away from coastal areas and bluffs, and removing barriers to the migration of plants and animals. These linked approaches highlight the need for greater emphasis on nature-based protection strategies or buffers. Low cost behavioral actions can provide benefits within a short time.

There are many strategies and approaches to climate change adaptation, which include decreasing vulnerability, increasing resilience, increasing adaptive capacity, and/or decreasing the risk of impacts (high agreement, high evidence). [15.2.3] Decreasing risk, especially for developed countries, has been planned by a top-down approach including engineered infrastructure-based solutions such as dikes to prevent flooding and coastal inundation and dams to improve water supplies. Strategies adopted in developing countries, e.g., those in NAPAs, are almost identical with standard development projects. Bottom-up approaches are particularly useful in efforts seeking to reduce social vulnerability and addressing adaptation to climate change as a process. However, adaptation to climate change also requires complementary top-down strategies through different levels of governments to realize mainstreaming adaptation. Adaptation planning also highlights the importance of intergovernmental and multidisciplinary approaches integrating science and planning.

A no-regrets co-benefits approach of improving resilience through an emphasis on disaster risk reduction has become increasingly common. (high agreement, medium evidence). [15.2.3.2,] Disaster risk reduction (DRR) includes managing hazards from extreme weather events and helps communities to deal with the uncertainty of climate change. Climate change adaptation and disaster risk reduction are within separate agencies, although they share similar objectives and challenges, and there must be an effort towards better coordination. On the other hand, disaster risk management strategies by themselves often fail to account for a wide spectrum of threats and scales needed for climate change adaptation. The root causes of climate change vulnerability cannot be addressed through risk management alone. Due to the uncertainty, dynamic complexity, and short to long timeframes associated with climate change, robust adaptation efforts require iterative risk management strategies.

A variety of tools are being employed in adaptation planning and implementation depending on social and management context (high agreement, robust evidence). [15.2.4] Uncertainties in climate change coupled with the complexities of social-ecological systems requires adaptation planning and implementation are dynamic. Information and knowledge on climate change risks from various stakeholders and organizations are essential

resources for making adaptation planning. Multidisciplinary efforts have been engaged to develop, assess and communicate climate information and risk assessments across timescales. These efforts use a mixed portfolio of products from simple agroclimate calendars to computerized decision-support tools. Although a wide range of adaptations are possible with current technologies and management practices, development and diffusion of technologies can expand the range of adaptation possibilities by expanding opportunities or reducing costs. The status quo generally requires no new capital costs and may be more profitable in the short term than developing more climate-resilient technologies. Monitoring and early warning systems play an important role in helping to adjust adaptation implementation, especially on the local scale.

Adaptation planning and implementation is considered as a social learning process to formulate efficient plans, which allows periodical adjustments in order to reduce the uncertainty of the impacts of climate change and societal needs to cope with them (high agreement, medium evidence). [15.3.3] Social learning is a relevant but under-investigated feature of planning and a critical part in the innovations for adaptation. Understanding of why and how learning takes place is needed to improve the impact and efficiency of the plan, improve the transferability of best practices, increase public support, and translate the learning into new plans. Monitoring and evaluation are two important learning tools in promoting this process. Although the importance of evaluation in adaptation is recognized, this topic is under-researched and requires significant work.

Adaptation governance plays a key role to promote the transition from planning to implementation of adaptation. (high agreement, medium evidence). [15.4] The role of governance is highlighted in building adaptive capacity to climate change, providing the connections between individuals, communities, organizations, agencies, and institutions at multiple levels and in articulating top-down or bottom-up perspectives. As a multidimensional issue involving many state and non-state actors functioning on varying scales of global, national and local levels, a coordination of roles and responsibilities enhances institutional networking for effective implementation of climate change adaptation. Multilevel governance offers the chance to identify options for switching from reactive to proactive adaptation processes which are essential in safeguarding investments and infrastructures especially in urban adaptation. The creation of larger governance networks through coordination is reported to expand the adaptive capacity of local actors, as well as enhancing learning opportunities for policy formulations.

15.1. Introduction

As impacts of climate change have become apparent around the world, adaptation has attracted increasing attention. The impacts are expected to be particularly severe in the developing world and among marginalized communities because their adaptive capacity is limited. Until the mid-1990s, research on climate change focused almost exclusively on understanding of climate system dynamics and modeling of future climate. More recently, several programmes have been developed that give more prominence to studies of vulnerability and adaptive capacity and associated adaptation options, measures and strategies, including local, regional, and sectoral studies.

Chapter 17 of the IPCC Fourth Assessment Report (AR4) (Adger et al., 2007) presented the following major findings on adaptation practice:

- Adaptation to climate change is already taking place, but on a limited basis.
- Adaptation measures are seldom undertaken in response to climate change alone.
- Many adaptations can be implemented at low cost, but comprehensive estimates of adaptation costs and benefits are currently lacking.
- Adaptive capacity is uneven across and within societies.
- There are substantial limits and barriers to adaptation

There are many definitions and characteristics of adaptation strategies and varieties of implementation (Carter et al., 1994; Burton et al., 2005, Biesbroek et al., 2010). For the purpose of this chapter, adaptation strategies in general are defined as a general plan of action for addressing the impacts of climate change, including climate variability and extremes. It will include a mix of policies and measures with the overarching objective of reducing the country's vulnerability. This chapter will review the literature on climate change adaptation to assess the progress and limitations of adaptation planning and implementation. As the Fifth Assessment Report of the IPCC Working Group

II has four inter-related chapters for adaptation, this chapter focuses on the assessment of cases at different levels, from international to local in various sectors to assess:

- The resent status of climate change adaptation planning and implementation across the globe. The practices of adaptation planning and implementation have extended from international and national to local levels, and different sectors (e.g., disaster risk reduction, water resource planning, agriculture, urban planning) treat adaptation within their traditional context of planning to various degrees.
- Characteristics of adaptation in different settings. Adaptation planning characterizes decision-making under the uncertainty of climate change projections, other climatic factors, as well as societal changes in the long term. Countries take different strategies and approaches such as low-regret policy, climate proofing approach, science-driven and community-based approaches. Flexible and adaptive approaches are also emphasized. To understand the characteristics of the strategies and approaches to adaptation is also a challenge of this chapter.
- Barriers and opportunities for adaptation. It has been indicated that there are substantial limits and barriers to perform adaptation planning and implementation whereas the opportunities are also recognized. This chapter tries to identify the barriers to and opportunities for adaptation in developing and developed countries.
- Capacities for adaptation and how are they built? Capacities for adaptation planning and implementation are wide including institutional and financial abilities, capacities to access and use scientific information, technologies, decision-making measures, human resources and social awareness.
- Governance of adaptation. As adaptation has a wide range of stakeholders, its success or failure depends on governance, which is quite complicated because of many reasons. How climate change adaptation is being coordinated across different levels of governance is a key question regarding this subject.

Following national and region-specific syntheses (Biesbroek et al., 2010; Bierbaum et al., 2013), the Chapter highlights factors motivating and facilitating the development of adaptation strategies; the scientific and technical information, support and collaborative mechanisms being used for the development and implementation; promotion of climate change awareness and strategies through communication; present and evolving forms of multi-level governance and responsibilities to implement the proposed actions, mechanisms and arrangements for incorporating adaptation into integrated management and sectoral actions; and how the strategies and their implementation are being evaluated.

Figure 15-1 shows a general cycle of adaptation and the environment it occurs. It has major components of adaptation planning and implementation and this chapter will discuss them in the following sections.

[INSERT FIGURE 15-1 HERE
Figure 15-1: Four main phases of adaptation planning and implementation: needs, planning, implementation, and evaluation. This is a cyclic, iterative process. Building capacity to respond to change, whether expected or unexpected, creates resilience in societies to cope in the face of uncertainties in climate change projections. Efforts in adaptation need to be linked with development or disaster risk management. This is particularly true and important in developing countries. Adaptation governance underlies the capacity and governance takes place at multiple scales: international, national, sub-national, and local.]

15.2. Status of Adaptation Planning and Implementation

The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised the importance of adaptation to climate change. These efforts have fostered a growing number of adaptation responses in developed and developing countries. The assessment of literature indicates adaptation planning is transitioning from a phase of awareness and promotion to the development and construction of adaptation responses. This transition represents a positive trend compared to earlier IPCC reports, it is not clear yet how effective these responses currently are and will be in the future. Despite the current dynamics of adaptation planning, there are still limited evidence of its implementation that is readily identifiable from development and disaster risk reduction plans.

The review of the international literature identifies a high heterogeneity of adaptation planning. The heterogeneity is related to the context specific nature of adaptation, but also to the differences in resources, values, needs, and perceptions among and within societies. The diversity of adaptation strategies, plans and actions at the national, subnational, and local level indicates differences in approaches between developed and developing countries. Although attention to climate change impacts and disaster risk management are key elements of adaptation planning, they appear to have a more prominent role in developed countries. In contrast, the literature reflects a trend to link adaptation planning to development needs and stresses in developing countries. This has had implications in terms of the resources and institutional needs to support adaptation planning and its implementation in developed and developing countries.

Although more attention is being paid to the institutional dimension of adaptation, it remains an underdeveloped area. Embryonic discussions of the transformations needed in the structure and operational culture of institutions to address adaptation to climate change are occurring in both developed and developing countries. Researchers have been reporting on the limitations of current institutional arrangements to support the implementation process of adaptation, critically so at the local level. Other unintended consequences include the difficulty to mainstream adaptation planning and delays in its implementation as a result of the mismatch of organizations and responsibilities.

Central to this discussion and one of the critical aspects identified in the review of the international literature is the trend to consider adaptation planning as a problem-free process capable of delivering positive outcomes. There is the risk of underestimating the complexity of adaptation planning as a social process. This can lead to creating unrealistic expectations in societies, and overestimating the capacity of planning to deliver the intended outcome of preparing societies to adapt to the negative impacts of climate change. This highlights the importance of monitoring, evaluating and reviewing adaptation planning and implementation.

15.2.1. Responding to Present and Future Climate Impacts

The international literature reports the dynamic creation of plans, strategies, legislation and projects at national, subnational, and local levels (Bulkeley, 2006; Biesbroek, 2009; Romero-Lankao and Dodman, 2011). The number of adaptation plans and strategies has grown at the national and subnational level in high-income countries, but at a lower pace in low and middle-income countries. Berrang-Ford et al. (2011) document a sharp increase in the peer-reviewed literature addressing adaptation to climate change (1741 articles published between 2006 and 2009). Preston et al. (2009) identify at least 62 different adaptation plans publicly released in the United States, Canada, United Kingdom and Australia, and they expected that number would double by the end of 2009. Tompkins et al. (2010) document over 300 adaptation actions in the UK in 2005. The non-peer reviewed literature reports a dynamic growth of adaptation plans and strategies at the national, subnational, and local level. A significant number of those publications are descriptive and provide limited information on the progress made so far in adaptation planning and its implementation.

The international literature has begun to pay attention to the need for improving the understanding of adaptation processes. Berrang-Ford et al. (2011) highlights the limited understanding of these processes and how adaptation planning is actually taking place. The majority of studies on adaptation to climate change report on the assessment of potential vulnerability of the social and natural systems to the negative impacts of climate change. They note that most publications describe an intention to act rather than concrete adaptation actions. In a review of adaptation articles in the journal Climatic Change Arnell (2010) as well concludes that very few published examples of case studies of how adaptation to climate change is actually being delivered, or on the barriers that will influence how adaptation takes place. Tompkins et al. (2010) question whether the observed adjustments and changes to perceived climate risks represent evidence of a societal shift towards a well-adapting society, or are merely unconnected actions of individuals motivated by different stimuli. Other studies report little research has been carried out on climate change adaptation actions to date as distinguished from determinants of adaptation capacity (National Research Council, 2011).

Some literature has focused on the social dimension of adaptation and adaptation planning. Orlove (2009), Ribot (2010), Boyd and Juhola, (2009) and others observe that adaptation analysis and many recommended measures tend to focus on the physical hazards rather on than on the underlying stressors creating them thus neglecting the drivers of vulnerability, and thus, limiting the effectiveness for interventions. Hardee and Mutunga (2010), Lemos et al. (2007), and Sietza et al. (2011) indicate that the disproportionate focus on the impacts of climate change could obscure opportunities for connecting development pressures, poverty, social inequality and climate change, particularly for the reduction of social vulnerability. Hulme et al. (2009), Barnett and Campbell (2009) suggest knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions, partly due to the context specificity of adaptation. Thus Sanchez-Rodriguez (2012) highlights the need to build operational approaches of adaptation planning by recognizing the structural socio-economic conditions and agency of individuals and communities in low and middle-income countries. These studies follow on decades of research and practice in the disaster risk reduction field (Blaikie et al., 1997; IPCC, 2012) and shows positive examples of the adaptation research community beginning to learn from other long-standing disciplines.

Attention to the social dimensions of adaptation, including rates of change in social conditions, in part of the international literature coincides with the interest of international organization and scholars in the relationship between adaptation and development. The literature supports the long-standing contention that adaptation takes place as a response to multiple stimuli - not just climate (IPCC, 2007; Tompkins et al., 2010). The importance of climate adaptation is also influenced by how the issue is framed. For example, to the extent that it is viewed as a public safety issue or a development issue, it may have greater resonance within local government (Measham et al., 2010). Other authors consider integrating local knowledge and experience, including households, into multidimensional and multi-scale approaches to guide the construction of adaptation responses to climate change, and integrate them with development strategies (Ewing et al., 2008; Moser and Satterthwaite, 2008; Hodson and Marvin, 2009). Stringer et al. (2009) consider that the linkages between adaptation and development should be made more explicit. Dovers (2009) stresses the need of connecting climate adaptation more closely to existing policy and existing agendas, knowledge, risks, and issues communities already face.

Important steps for mainstreaming adaptation have been identified but the challenges remain in their operationalization within the current structures or operational cultures of national, subnational and local agencies. Multilateral Development Agencies encourage efforts in this direction through a number of guidelines, publication and development assistance (UNDP, 2005; USAID, 2007; OECD, 2009; UNEP, 2010; World Bank, 2010; UN-HABITAT, 2011). Central to these efforts is the role of planning that connects adaptation and development needs and challenges (Blanco and Alberti, 2009; Dovers, 2009; Juhola and Westerhoff, 2011). Urban, regional, and development planning have struggled to create interdisciplinary perspectives to address the multidimensional reality they seek to modify. This issue will be addressed in more detail in section 15.3.1.2 within the context of institutional arrangements.

15.2.2. International, National, and Local Assessment

15.2.2.1. International Mechanisms for Supporting Adaptation Planning

There has been a large growth of adaptation planning initiatives at the international, national, subnational, and local level since the last IPCC report (UK, Germany, Australia, Canada, the Caribbean among others). The assessment of the literature illustrates a diversity of approaches that have evolved in adaptation planning across and within countries, the challenges to create multilevel governance to support dynamic adaptation planning and implementation, the central role of climate change impacts and risk management in adaptation strategies and plans, and different perceptions, resources, and approaches in these strategies and plans between developed and developing countries. Many of these adaptation initiatives are at an embryonic state and it is difficult to extract conclusions of their effectiveness, efficiency, and equity at this point. The dynamic pace of the creation of adaptation strategies and plans stresses the importance of monitoring and evaluation. While the Adaptation Fund and Pilot Program in Climate Resilience have outlined monitoring and evaluation criteria, little is found in the literature to support effective and sustained implementation of these two dimensions (Adger et al., 2009b; Preston et al., 2009; Tompkins et al., 2010; Wolf et al., 2010).

15.2.2.1. International Mechanisms for Supporting Adaptation Planning

International mechanisms for supporting regional adaptation planning are an important resource for the creation of adaptation responses. The directives and initiatives of the European Commission (EC) have fostered the creation of a significant number of National Adaptation Strategies and Plans in EU member countries since the last IPCC report. Adaptation planning responses at the local level have also multiplied in these countries in response to these directives. Other relevant regional initiatives are the South Pacific Regional Environmental Programme (SPREP) supported by a number of international agencies, and in the Caribbean through the Caribbean Catastrophic Risk Insurance Facility (Pulwarty et al., 2010).

The international literature reports a growing number of mechanisms developed by Multilateral Development Organizations, development cooperation agencies from Developed countries (UK, USA, Canada, Sweden, Denmark, Norway, Japan, Spain, the Netherlands among others), United Nations programs (UNDP, UNEP, UN-HABITAT, WMO, FAO and other agencies), and International Non-Governmental Organizations (OXFAM, CARE, IFRC, ICLEI and others). These organizations focus on their particular geographic and thematic areas of interest. An example in the case of development agencies is the collaboration between the UK and Canada (IDFG and IDRC) to create the Climate Change Adaptation in Africa (CCAA). This initiative supported 46 projects mostly in rural areas of several countries. The initiative focused on three areas: participatory action research, communication and networking, and networking education and training. Development agencies have also supported adaptation planning in a number of developing countries in Africa, Asia, and Latin America, the South Pacific, and the Caribbean.

Multilateral Development Agencies (MDA) have developed mechanisms to mainstream climate change in their project planning. They have created guidelines and provided support for adaptation planning in developing countries. Some MDA focus on guidelines for the creation of adaptation projects (USAID, 2007), other highlights the importance of integrating adaptation planning with development co-operation (OECD, 2009). The World Bank has led the systematic examination or 'portfolio screening', of its set of policies, programs or projects, with the aim of identifying how concerns about climate change can be combined with an agency's development priorities, such as poverty reduction, institutional development and capacity building (Klein et al., 2007; World Bank, 2010).

The United Nations Development Programme (UNDP) has a broad range of mechanisms supporting adaptation planning, including guidelines (UNDP, 2005), information resources, support to national adaptation planning, and as an implementation organization in some of the early projects approved by the Adaptation Fund. Together with the United Nations of Environmental Programme (UNEP) provide support to Sub-Sahara countries in Africa through the Climate Change Development Initiative (CCDARE). Other UN agencies have created information mechanisms supporting adaptation planning. Particularly relevant are the activities United Nations Framework Convention on Climate Change for least developing countries through the National Adaptation Programmes of Action (NAPAs) and for less developed countries through the National Adaptation Plans (NAPs) discussed in the next section.

Relevant funding mechanisms are associated with the Global Environmental Facility (GEF) adaptation funds (LDCF and SCCF), support for the Pilot Program for Climate Resilience (PPCR), and special purpose adaptation funds for UN Agencies. The Adaptation Fund (AF) set up under the Kyoto Protocol is of particular importance to developing countries as it is pioneering the direct access mechanisms, which allows countries to access funds without having to work through a multi-lateral development agency. The AF indicators suggest a focus on addressing the adaptation deficit and climate -proofing development for incremental changes in existing risks while the PPCR framework has a stronger focus on the mechanisms through which adaptation is integrated into development planning and practice.

International non-governmental organizations has growing presence fostering adaptation planning in developing countries. Large organizations have created diverse mechanisms to support adaptation at the local level. For example, Oxfam America has developed a risk management framework with enable poor farmers in Ethiopia to strengthen their food and income security through a combination of improved resource management (risk reduction), microcredit ("smart" risk taking), risk transfer (insurance), and risk reserves (savings). Oxfam has also published guidelines to support local adaptation planning (Crane, 2013). The International Federation of Red Cross (IFRC)

have extensive mechanisms focusing on disaster risk management and vulnerability reduction and its integration with climate change adaptation (IFRC, 2009; Braman et al., 2010). CARE has also extensive mechanisms addressing climate change adaptation and community resilience (Action Aid, CARE, WWF, 2012). It is worth mentioning a number of other International NGOs have created mechanisms to support adaptation planning at the local level in developed countries (ICLEI, 2008; Pew Center, 2009).

Information centers have also arisen with guidelines, information, case studies, and other support tools to facilitate adaptation planning by MDA, UN agencies, and international NGOs. Some of these center are: IFRC's Climate Center, CARE's Climate Change information Center, World Bank Adapt, UNDP Adaptation Learning Mechanism, and weAdapt of the Stockholm Environmental Institute.

The fast growth of international mechanisms for supporting adaptation planning has assisted the creation of adaptation strategies, plans, and actions at the national, subnational and local level. The international literature documents a growing number of projects sponsored through these mechanisms. Their monitoring and evaluation can help sponsoring organizations, stakeholders, and government agencies to extract learning lessons to increase and improve the efficiency of adaptation planning and implementation. It is worth noting that so far little attention has been provided to critical reflections during the adaptation process.

15.2.2.2. National Adaptation Plans

The IPCC Fourth Assessment Report documented the international recognition of the importance of adaptation to climate change. This is reflected in the growing number of national governments creating national adaptation strategies, policies, and plans. The international literature illustrates the diversity of approaches used in these national initiatives, from National Adaptation Programmes for Action (NAPAs) in least developed countries targeting key sectors (Ciplet at el., *in press*), to the efforts to create national holistic plans in response to regional directives in some European countries (Biesbroek et al., 2009, 2010). The NAPA focus on existing coping strategies and actions at the grassroots level in Least Developed Countries (LDCs) , and build upon that to identify priority activities, recognizing that local communities are the main stakeholders. At the same time, the movement to introduce climate change adaptation policies into national policies has accelerated in the developed countries as well. National adaptation initiatives and their heterogeneity reflect the idiosyncrasies of the domestic political structures, socio-economic conditions, values and perceptions, and development stresses and opportunities.

The analysis of the international literature identifies national governments assume a coordinating role of adaptation actions in subnational and local levels of government. Early evidences suggest that some of the coordination roles of national governments include: the provision of information of potential impacts risks to strengthen actions of state and local governments, providing policy frameworks to guide decisions at subnational level, driving and coordinating the creation of legal frameworks, direct action in case of sectors and resources key for national development (agriculture, fisheries, health, ecosystem protection, among others), actions to protect vulnerable groups, and financial support to other levels of government. In some cases, national governments are key actors securing international funding for subnational and local levels of government. Despite the embryonic state of the adaptation process, an assessment of the characteristics and effectiveness of the coordinating role of national adaptation strategies and plans is an urgent pending task.

National adaptation is an evolving process. Thirteen European countries have created National Adaptation Strategies—Austria, Belgium, Denmark, Finland, France, Germany, Hungary, the Netherlands, Norway, Portugal, Sweden, Spain, United Kingdom (only two of them were created before the last IPCC report, Finland and Spain) (Prutsch et al., 2010). Some of these strategies have evolved to a National Adaptation Plan (France, Germany, UK). While these may represent a new political commitment to adaptation at national political levels (Biesbroek et al., 2010) , many institutional challenges and barriers to future policy implementation remain. Many projects do not have defined an implementation agency (Swart et al., 2003). Australia's federal government has invested in research through CSIRO Climate Adaptation National Research Flagship and the National Adaptation Research Facility and supports local government's climate change adaptation role (Local Adaptation Pathways Program). However, a governance system integrating adaptation planning across all levels of government is still pending (Doran, 2011).

Some countries recognize the learning process of adaptation and have programmed the evaluation of their national adaptation strategies and plans (UK, Germany, Australia among others). The federal government in Mexico has taken steps to update its National Adaptation Strategy from 2007 (Gobierno Federal, 2012). Although these steps update and upgrades adaptation planning, there remain obstacles for their implementation. Within the U.S., as in other areas, although substantial adaptation planning is occurring in various sectors, levels of government, and the private sector, few measures have as yet to be implemented and fewer have been evaluated (Bierbaum et al., 2013).

The experience resonates with the perspective that most strategies can be regarded as just the start of a policy process rather than its culmination emphasizes the importance of considering evaluation planning and its implementation a learning process (Hulme et al., 2009; Biesbroek et al., 2011; Pulwarty et al., 2012).

Institutional obstacles affect differently the coordinating roles of national adaptation strategies and plans. Particularly affected are the creation of policy frameworks to guide decisions at subnational and local level and the integration of adaptation in sectorial policies. Evidence of this problem begins to be addressed in some studies. The ADAM project in Europe considers most barriers to actual adaptation to be related to policy co-ordination and implementation (Hulme et al., 2009). Particularly challenging is multi-level coordination within with other levels of government and between the government and other sectors in society. Multi-level governance is a challenge in developed and developing countries (Storbjork, 2007; Unwin and Jordan, 2008; Gupta et al., 2010; Gero et al., 2012; Rodima-Taylor et al., 2012). Early identification of these barriers and actions to address them are part of the pending task in national adaptation strategies and plans. Governance structures have seldom efficient multi-level practices despite decades of development planning. This remains a major obstacle to achieve efficient adaptation planning and implementation. Sections 15.3.1.1 and 15.3.1.2 address this issue further.

National Adaptation Programmes of Action (NAPAs)

National adaptation responses have a particular condition in the case of the Least Developed Countries through the experience of UNFCCC's NAPAs (National Adaptation Programmes of Action). Established in 2001, NAPA is an organized planning process for adaptation sponsored by the United Nations Framework Convention for Climate Change (UNFCCC) (Ciplet *et al*., in press). As of November 2010, the UNFCCC Secretariat received forty-seven NAPAs.

The international literature stresses the reliance on this program (Agrawal, 2008; Agrawal and Perrin, 2008; Stringer et al., 2009). The NAPAs have emphasized the connecting local level adaptation and development. More than 50% of the projects under this program are concentrated in three key sectors for development and livelihoods: food security, terrestrial ecosystems and water resources. One study of NAPAs in four African countries illustrates that they are attracting the support of a greater range of actors but linkages between development and adaptation need to be made more explicit (Stringer et al., 2009).. They find the enthusiasm for broader participation in the rhetoric of international politics does not yet match the realities of its enactment on the ground. Another study identified only 20% of projects described in the NAPA documents that incorporate local institutions as the focus of adaptation projects and identified even fewer that incorporate local institutions as agents or partners in facilitating adaptation. The researchers, Agrawal and Perrin (2008) suggest that projects tend to build the capacity of national governments and agencies rather than local actors and local institutions still seems to be valid. Other authors document financial difficulties in NAPA projects leading to cumulative delays and the outdatedness of many of the needs first assessed (Ciplet at el., *in press*). Sustained monitoring , evaluation and feedback to learning of the NAPAs process are needed to help these countries transcend from a project by project basis to an adaptation process within the context of domestic and local development efforts.

15.2.2.3. Sub-National Adaptation Plans

The international literature has paid less attention to adaptation planning and implementation at the subnational level. There are major differences on the role subnational governments play in the governance structure of countries, from those with strong concentration of political and economic power to a very minor role in governance and decision-

making. The role of subnational governments in adaptation planning reflects the governance structure of each country.

The review of the international literature identifies subnational governments have often a complementary role to national governments in adaptation planning according to the governance structure in each country (Moser, 2005; West and Gawith, 2005; Lemmen et al., 2008; Pew Centre, 2009; USGCRP, 2009). Although the development of adaptation governance has not created guiding frameworks for subnational governments in most countries, the literature reflects an active participation of states and provinces in some countries. For instance, Gero et al. (2012) report all states and territories in Australia have begun creating or amending laws, policies, and action plans to account for climate change adaptation. The provincial governments in Canada have also an active role in the creation of adaptation planning. 24 out of 32 states in Mexico have created Climate Action Plans in the last 6 years with technical support from the federal government of Mexico and some financial support from international sources (Gobierno Federal, 2012). A growing number of states have created also climate actions plans that include adaptation actions in the United States.

In addition to state by state efforts, supra-state organizations are also recognizing, supporting, and fostering attention on adaptation, though concrete action to date is limited (Pew Centre, 2009). In some instances, states are collaborating on sector specific issues that concern them regionally (Bierbaum et al., 2013). For example, in the American West, water managers are collaborating and sharing information regionally (Brekke et al., 2009; Barsugli et al., 2012). Similarly, in the Great Lakes region, Midwestern states and Canadian provinces have expressed concern over the impact of climate change on their joint water basin (though concrete adaptive management actions have not yet been specified) (Dinse et al., 2009). Canada's Regional Adaptation Collaborative Program is also an example of regional collaboration of subnational governments. Further examples have appeared also across borders (for example, the Western Climate Initiative that includes 7 states in the U.S. and 4 provinces in Canada). Regional adaptation plans have also been created in European countries such as the Climate Change Adaptation Plan in East England (Staples, 2011). The embryonic state of these regional collaborations does not allow drawing conclusion of their operation and outcomes for this report. However, it is a process worth monitoring during the coming years.

15.2.2.4. Local Adaptation Plans

The international literature shows a significant increase in the number of planned adaptation responses at the local level in rural and urban communities of developed and developing countries since the last IPCC report. Climate adaptation is context dependent and it is uniquely linked to location, making it predominantly a local government and community level of action. However, limited economic, human, technical resources at the local level highlight the importance of national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders. Despite the obligation to act, local governments are hindered by the absence of applicable guides to adaptation decision-making, especially adaptation to extreme events (Corfee-Morlot et al., 2009; Glaas et al., 2010; Gero et al., 2012). Local councils and planners are often confronted by the complexity of adaptation without adequate access to guiding information, data on local vulnerability and the potential impacts of climate change. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes but without effective guidance on decision-making and the potential unanticipated consequences of those decisions (Mathew et al., 2012).

The central role of local governments addressing the challenges of adaptation planning and implementation is reflected in the literature (Blanco and Alberti, 2009; Sanchez-Rodriguez, 2009; Rosenzweig and Solecki, 2010; Simon, 2010; Matthews, 2012;), but scholars stress also the importance of partnerships between public, civic, and private in the adaptation process (Agrawal, 2010; Tompkins and Ealkin, 2012). The complexity and uniqueness of each locality is often not recognized by policy planners because of the lack of understanding and consultation with the local community (Geiser and Rist, 2009; Ribot, 2010). Inclusive and participatory approaches in adaptation planning are encouraged by international organizations (UNDP, 2005, 2010; World Bank, 2010; UN-HABITAT, 2011) and scholars (Moser, 2008; Moser and Satterthwaite, 2008).

15.2.2.4.1. Rural and community adaptation planning

Community-based adaptation, an example of local level planning and implementation, is a course of action that allows local stakeholders to bring skills and knowledge into the planning process. Because climate change impacts occur locally, the scale of community engagement and the approaches used have been critical to the success or failure of adaptation programs where they occur (Picketts et al., 2012).

Ford et al. (2011) examined adaptation plans that were implemented in developed nations from 2006 to 2009, and found that stakeholder participation was commonly mentioned as part of the planning process. Patt and Schröter (2008) document barriers to implementing climate change adaptation strategies in Mozambique that resulted from differing perceptions of climate risk between farmers and policy makers, and the perceived potential for negative consequences of the proposed adaptation plans. These studies suggest that without broader stakeholder agreement at the local level, successful implementation of adaptation is not possible. However, in other case studies of community-based participatory adaptation projects, local farmers such as those in Sri Lanka needed no additional incentives to participate in adaptation programs that they recognized as an opportunity to improve their harvests and income. The creation of community organizations can provide an avenue for local participation, and provides a mechanism that helps to sustain adaptation efforts. Community-based adaptation in Bangladesh has included participatory action plan development, an approach that combines consensus-building and participatory rural appraisal. The needs, skills and assets of the communities were assessed by conducting household surveys and consultation meetings (Ensor and Berger, 2009).

Indigenous and rural peoples, however, are not only potential victims of climate change. Attentiveness to environmental variability, shifts and trends is an integral part of their ways of life. Community-based and local knowledge continue to offer valuable insights into environmental change due to climate change, and complement broader-scale scientific research with local precision and nuance. Indigenous societies have elaborated coping strategies to deal with unstable environments, and in some cases, are already actively adapting to early climate change impacts (Nakashima et al., 2012). Indigenous Arctic communities are providing systematic observations of climate change impacts, which complement scientific data and frame local efforts to adapt.

Other authors have studied the role of the business community in adaptation planning. Howe (2011) notes the adaptive capacity of businesses vary with the types of business, location, and socio-cognitive characteristics of business owners. Other perspectives (Berkholt et al., 2006; Tompkins et al., 2010) suggest that market forces are unlikely by themselves to lead to efficient adaptation requiring public ploicy interventions. Other studies suggest business responses can be motivated by other forces. For example, the study of climate adaptation in the UK mentioned above found that responses to regulation, industry standards such as ISO14001, and corporate social responsibility obligations have at least as great an influence on adaptive behavior in the business community as direct climate-related risks and can produce public benefits (Tompkins et al., 2010)

15.2.2.4.2. Urban areas

A growing number of urban areas have created disaster management plans at the local level, often in response to climate-related disasters (OECD, 2010; Dodman, 2012; EEA, 2012). Few of these plans have incorporated climate change adaptation so far. The peer and non-peer reviewed literature reports a growing number of adaptation plans at the local level. Urban areas are the locus of a number of those planning initiatives (Roberts, 2008; Blanco and Alberti, 2009; Hamin and Gurran, 2009; Lowe et al., 2009; Parzen, 2009; Sanchez-Rodriguez, 2009; Corfee et al., 2010; Rosenzweig and Solecki, 2010; Rosenzweig et al., 2011; Matthews, 2012; New York, 2012; ; Rotterdam, 2012). This includes special issues in some academic journals (for example, papers included in the special issue Habitat International vol. 33, 2009 and Current Opinion in Environmental Sustainability vol. 2, 2010 and vol. 3, 2011). The non-peer reviewed literature also documents a growing number of adaptation plans to climate change in large cities (New York (2012), Chicago (2012), London (2010), Toronto (2008), Mexico City (2008), Sao Paulo, Rotterdam (2012)), but increasingly in medium-size cities (King County in Washington State, Santa Cruz in the US, Cartagena in Colombia (2005), Durban (2012) and Cape Town in South Africa (2006)) (note that this list of urban

areas is intended for illustrative purposes). The experiences in these cities provide early lessons potentially useful to other cities.

Chapter 8 discuses in detail the impacts, vulnerability and adaptation of climate change in urban areas. A review of the literature allow identification of the difference in the adaptive plans of urban areas (Romero-Lankao and Dodman, 2011; Rosenzweig et al., 2011; Carmin et al., 2012). These differences are particularly evident between urban areas in developed and in developing countries and they reflect diverse conditions, resources, perceptions, and governance structures among cities (Agrawala and van Aalst, 2008; Ayers, 2008; Bartlett, 2008; Caney, 2008; Moser and Satterthwaite, 2008; Revi, 2008; Roberts, 2008; Simon, 2010; Stren, 2008; Tanner et al., 2008; Hardoy and Pandiella, 2009; O'Demsey, 2009; Hardoy and Romero-Lankao, 2011;). The literature suggests that responding to current climate extremes and potential future impacts of climate change are primary determinants in the creation of adaptation plans (Rosenzweig and Solecki, 2010; Rosenzweig et al., 2011; Carmin et al., 2012). For instance, adaptation plans in London, Toronto, New York City, Chicago, Rotterdam focus on responses to the impacts of climate change and sea level rise with a strong emphasis on protective infrastructure.

As yet the extent to which adaptation plans in cities of developing countries will follow a similar approach or if they will consider the guidelines suggested by MDA and other international organizations to mainstreaming adaptation into municipal and development planning remains unclear (UNDP, 2005, 2010; USAID, 2007; World Bank, 2010). The difference in approaches to adaptation planning has implications for adaptation governance, institutional arrangements, resources, and stakeholders involvement in the adaptation planning process and its implementation. This is an issue that merits further analysis in the near future. Related to this discussion is the gap between disaster risk management and climate change adaptation in urban areas. Enforcing parallel agendas for disaster risk management and climate change adaptation runs the risk of duplicating efforts and resources, creating competing actions and potential conflicts with unintended negative consequences, including maladaptation. Anguelovski and Carmin (2011) suggest that few urban areas have the resources and know-how to institutionalize adaptation planning in developing countries. Section 15.3.1.1 addresses this issue further.

15.2.3. Strategies and Approaches

15.2.3.1. An Overview

Strategies include decreasing vulnerability, increasing resilience, increasing adaptive capacity, and/or decreasing the risk of impacts (Few et al., 2007; IPCC, 2012). Decreasing risk, especially for high-income nations, has furthered through with engineered infrastructure-based solutions such as dikes to prevent coastal inundation from sea-level rise, new dams to improve water supplies, and other designs to reduce flooding. These approaches have been implemented in European countries such as the UK, Germany, especially the Baltic Sea region, and in U.S. coastal cities such as San Francisco and New York (Hofstede, 2008; Garrelts and Lange, 2011; Rumbach and Kudva, 2011; Rosenzweig et al., 2011). In some case, such as flood risk planning, government policies have made implementing a diverse set of adaptation planning options more difficult because of the institutional preference for construction of large-scale protection designs (Harries and Penning-Rowsell, 2011). However, adaptation finance channelled through national governments is not likely to reach the lowest income and most vulnerable people, and infrastructure-based approaches to climate change adaptation often fail to include local residents in the adaptation planning process (Sabates-Wheeler et al., 2008; Rumbach and Kudva, 2011). In addition to the need to secure funding for infrastructure-related plans, implementation of top-down approaches can require numerous legislative and executive actions (Wheeler, 2008, 2011; Harries and Penning-Rowsell, 2011; Marino, 2011). In a review of adaptation planning for cities of the United States, planning for the effects of excessive heat in urban areas primarily consisted of future infrastructure changes, such as cool paving materials; but in actual heat-related emergencies, public health campaigns and community mobilization were necessary (Ebi and Schmier, 2005; O'Neill et al., 2010). During a 1999 heat wave in Milwaukee Wisconsin, USA, the coordination of 20 different agencies was involved, demonstrating the need for additional adaptation strategies in addition to infrastructure planning (O'Neill et al., 2010).

In contrast to top-down strategies to fortify infrastructure, there are local organizational and community-based approaches (Ensor and Berger, 2009; Pelling, 2011). Community participation in adaptation planning appears to be more common in developing countries where community level planning is more common (Ford et al., 2011). Public awareness campaigns have aided the adaptation process. In the case of farming households in the Nile basin of Ethiopia, Di Falco and Veronesi (2011) demonstrated that farmers that were better informed were more proactive, and more likely to adopt new technologies useful in reducing drought-related crop failure.

15.2.3.2. Disaster Risk Management and Adaptation

A no-regrets co-benefits approach of improving resilience through an emphasis on disaster risk reduction has become increasingly common. Disaster risk reduction (DRR) includes managing hazards from extreme weather events and helps communities to deal with the uncertainty of climate change (Mitchell et al., 2010; IPCC, 2012) Proponents of merging DRR with climate change adaptation also note that currently, climate change adaptation and disaster risk reduction are within separate agencies, although they share similar objectives and challenges. Current regional and international institutions that have merged DRR and climate change adaptation include CARICOM (Caribbean Community Comprehensive Disaster Strategy) and CHARM (Comprehensive Hazard and Risk Management) in the South Pacific (Mitchell et al., 2010). In Bolivia, the Intercooperation project, utilizes traditional knowledge to improve agricultural production and to provide better decision making in risk-management (Mitchell et al. 2010). On the other hand, disaster risk management strategies by themselves often fail to account for the differing spectrum of threats and scales needed for climate change adaptation. A critique of climate change and disaster risk efforts in Canada by Etkin et al. (2012) showed that the root causes of climate change vulnerability cannot be addressed through risk management alone.

The need for better coordination between risk management agencies and climate change adaptation efforts is exemplified by the current dilemma faced by the Inupiat village of Shishmaref, Alaska. Village inhabitants are descendants of indigenous nomadic people that established a post-colonial sedentary community in response to government modernization, infrastructure development, and the need to send their children to school. Currently, the village and island where it is situated are experiencing increased flooding and high rates of coastal erosion (United States General Accounting Office (USGAO), 2009). The village has failed to find the funding needed to relocate, even though the community has rights to land off the island in a safer location. Planners, researchers and advocates have worked unsuccessfully with multiple government agencies in order to plan and organize relocation (Marino, 2011), because recovery funds are tied to rebuilding infrastructure in the same location without upgrades.

A recent Foresight project report on migration and environmental change (2011) examined the drivers of migration in 30 countries, and although the reasons for migration were multi-faceted, the primary driver of migration was economic adversity (Foresight Government Office for Science, 2011). Although economic changes can be produced by climate change impacts, the two are not always coupled. Tidal flooding in Semarang, Indonesia has not resulted in migration, even though communities affected by flooding are middle-income, and assumed to have the financial capacity to move. Some families, who own their land, are not abandoning their homes even when flooding becomes an everyday occurrence (Harwitasari and van Ast, 2011).

15.2.3.3. Adaptation, Development, and Ecosystems

International organizations are increasingly emphasizing the important relation between adaptation to climate change and development (UNDP, 2005; OECD, 2009; UNEP, 2010; World Bank, 2010; UN-HABITAT, 2011). IPCC (2012), Boyd and Juhola (2009) and others illustrate that the debate of climate change is dominated at present by impacts-led approaches that focus on climate risks rather than on human vulnerability. Knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions, partly due to the context specificity of adaptation which makes detailed planning at the national level challenging (Hulme et al., 2009). Dovers (2009) highlights the importance of connecting climate adaptation more closely to existing policy and management in communities, professions, and agencies, and to their existing agendas, knowledge, risks, and issues they already face.

Adaptation to climate change can be viewed as a continuous learning process (not a single outcome) likely to require regular revisiting of development policies, plans and projects as climate and socioeconomic conditions change (Hinkel et al., 2009; Hofmann et al., 2011). Most strategies can be regarded as just the start of a policy process rather than its culmination (Hulme et al., 2009). Projects in Asia implemented by the Global Environment-Least Developed Country Fund have linked adaptation efforts with development, and allowed for a holistic approach that builds institutional resilience, flexible technologies, and enhanced community capacity (Sovacool et al., 2012).

Research has long shown that coupling adaptive improvements in infrastructure with governance and community welfare, improved community resilience by enhancing local ownership, and created organizations increases adaptive capacity (IPCC, 2012). Climate change adaptation efforts also improve ecosystem resilience by implementing sustainable forestry quotas, expanding floodplain setbacks, implementing coastal afforestation, coral reef propagation, restoring degraded lands, maintaining healthy vegetation on slopes, incentivizing development away from coastal areas and bluffs, and removing barriers to the migration of plants and animals, (Sovacool et al., 2012). Increasingly, the good practices of planning and implementing integrated coastal and watershed management measures have been shown to apply equally to climate change adaptation (Tobey et al., 2010). These linked approaches highlight the need for greater emphasis on nature-based protection strategies or buffers. Adaptation efforts in Bangladesh, Cambodia, Bhutan, and the Maldives that are embedded in the development context are providing a 'win-win' adaptation strategy that improves resilience to climate change while improving economic stability and environmental quality. Even though the funds invested in adaptation linked to development is relatively small ($40 million in 2007), the Asian Development Bank estimates that every dollar invested could yield as much as $40 in economic benefits in twenty years (Sovacool et al., 2012).

Examples of such measures include: developing early warning information systems, health/heat action plans, vaccination, health system planning, flood risk planning, drought and water scarcity risk management, water demand management, coastal and flood defenses, economic diversification, natural hazard monitoring, reinforcing the built and green infrastructure environments (e.g. roads, bridges, electric wires, wetlands, land-use (IPCC, 2012).

In spite of the many positive attributes of community-based and development-based adaptation efforts, there are concerns that a disproportionate focus on the impacts of climate change could obscure opportunities for connecting development pressures, poverty, social inequality and climate change, particularly for the reduction of social vulnerability (Lemos et al., 2007; Hardee and Mutunga, 2010; Sietza et al., 2011). Other authors consider it critical to wholly integrate knowledge and experience into multidimensional and multi-scale approaches in order to guide the formation of adaptation responses, and effectively combine them with development strategies (Ewing et al., 2008; Hodson and Marvin, 2009). Moser and Satterthwaite (2008) propose considering the roles of not only different levels of government but also individuals, households, and civil society organizations. They suggest a framework of pro-poor asset adaptation for climate change as a conceptual and operational framework. Moser (2008) proposes a second-generation asset-based policy as an effort to sustain current poverty reduction policies focusing on the provision of housing, urban services and infrastructure, health, education and microfinance.

15.2.3.4. Stakeholder Participatory Approaches

Both procedural and distributional equity in adaptation requires considering the spread of adaptation benefits, costs, and residual climate impacts across regions, sectors, and population groups and peoples access and capability to take advantage of those benefits. Thomas and Twyman (2005) highlight the fact that climate change does not occur independently of other social processes. Despite the fact that social change is a central element of development, there is inadequate not attention paid to livelihoods in development studies to connect adaptation, vulnerability, and development (Paavola, 2008b; Sanchez-Rodriguez, 2009).

To address vulnerabilities to climate change, stakeholder participation is essential so that local impacts can be addressed and coping mechanisms including social and cultural capabilities are recognized and employed. Lyytimäki (2011) examined the role of national-level media coverage in Finland in relation to disseminating climate policies. Their work showed that the majority of news that mentioned climate change actually focused on additional

issues of culture, economy, and lifestyle issues. Marshall et al. (2010) examined the reasons behind sub-optimal adoption of seasonal forecasts by livestock owners in Queensland, Australia, and found that environmental awareness as well as social factors significantly influenced their willingness to adopt new grazing practices.

Stakeholder participation takes many forms, including integration of climate change impact scenarios in local decision making processes (Romanenko et al., 2007; Schmidt-Thomé and Kaulbarsz, 2008; Gawith et al., 2009). One example, in the Baltic Sea Region, includes two projects referred to as Sea level change affecting the spatial development of the Baltic Sea Region (SEAREG), and Developing policies and adaptation strategies for climate change in the Baltic Sea Region(ASTRA) that focused on integration of potential climate change impacts in local decision making. The resulting communication process produced a set of tools referred to as Decision Support Frame (DSF). The DSF addresses uncertainty in climate change model results, but also includes a vulnerability assessment and a discussion platform to help identify stakeholders, and to clarify climate change impacts and downscaled model uncertainty (Schmidt-Thomé and Kaulbarsz, 2008). Challenges addressed in the project included the explanation of the creation, application and uncertainty of complex climate models, as well as the inclusion of social scientists into applicable communication and application frameworks for climate change adaptation strategies. The ASTRA project followed the winter storm of January 2005, and was tasked with identifying what stakeholders perceive as the biggest potential impacts from climate change. The task of ASTRA is the sustained result of SEAREG by continuing awareness-raising efforts, and the development of adaptation strategies based on SEAREG scenarios (Schmidt-Thomé and Kaulbarsz, 2008).

15.2.4. Adaptation Tools and Decision Support Processes

15.2.4.1. An Overview

Uncertainties in climate change coupled with the complexities of social-ecological systems require adaptation planning and implementation are dynamic. Information and knowledge on climate change risks from various stakeholders and organizations are essential resources for making adaptation planning. Several multidisciplinary efforts, some of which are discussed below, have been engaged to develop, assess and communicate climate information and risk assessments across timescales. These efforts use a mixed portfolio of products from simple agroclimate calendars to computerized decision-support tools.

15.2.4.2. Science Supporting Adaptation Planning and Implementation

Adaptation planning and implementation takes place in a dynamic form on local, regional or global scales with complex management and governance processes, need to be implemented (Moser, 2009). The degree and type of feedback of a social-ecological system to climate change for planned adaptation measures are the major indicators of concern. (e.g. Berkhout et al., 2006). It has also long been recognized that adaptation is embedded within a process of social learning (IPCC, 2007, Ch 17) requiring the integration of science and policy in a fundamental and structured way.

Some of the earliest evidence of U.S. states beginning to address and plan for the impacts of anthropogenic climate change comes from states which had received federal financial and/or technical assistance to assess impacts and vulnerabilities and from existing concerns with climate variability or in response to experiencing severe climate-related disasters such as from ENSO (Miles et al., 2000; Moser, 2005; Pulwarty et al., 2009). In the U.S. the Regional Integrated Sciences and Assessment for academically led, Federal funded mechanisms to The Regional Integrated Sciences and Assessments (RISAs) have developed as decentralized scientific applications and policy experiments (Brunner, 1996) centered at Universities basis for a collaborative framework between monitoring, research, and management networked at regional and local levels (Pulwarty et al., 2009; Bierbaum et al., 2013). RISAs are somewhat different from other such knowledge management and applications efforts having been initiated out of a need to provide information on climate extremes and variability before moving out to climate change. Evolutionary or learning-based approaches to “assessment” such as designed and developed by RISA-type programs have proven effective at entering into national, regional and local plans of action for responding to

complex environmental problems than traditional, discrete integrated knowledge assessments (Pulwarty et al., 2009).

In UK, a national program was developed to access climate impacts across the country and to incentivize adaptive behavior since 2005 (Pringle, 2011). In Australia an interdisciplinary program was developed by the federal government to carry out adaptation activities through the NCCARF – National Climate Change Adaptation Research Facility. Government of Canada Regional Adaptation Collaboratives program, which supported science research for creation of adaptation plans (http://www.nrcan.gc.ca/earth-sciences/climate-change/community-adaptation/regional-collaborative/48). This program was instrumental in catalyzing further advancement and generated some comprehensive adaptation plans for regions across Canada. In Canada the OURANOS Consortium produces projections of regional climate trends and offer expertise in climatology and climate simulation.

The Caribbean Community and Common Market (CARICOM) with collaboration from the Organization of American States established the Caribbean Community Climate Change Centre (5Cs) in 2005 to guide the development of regional adaptation planning and implementation in the Caribbean. The 5Cs coordinates funding and provides guidance to regional impacts assessment and adaptation efforts. These include supporting critical capacity in regional climate modeling and sea-level monitoring, embedding climate risk information into environmental impacts statements, conducting and mainstreaming vulnerability and capacity assessments into national and local planning, facilitating within-country networks and to a Masters Degree program with a specialization in climate policy and impacts assessment. Climate adaptation has also been top issues in Mountainous areas and a series of relevant activities have been carried out (http://www.icimod.org/ and http://mri.scnatweb.ch/).

Local communities and NGOs are demanding an increasingly active role of public institutions in the delivery of technological options to cope with emerging climate challenges (Prowse and Scott, 2008; Rodima-Taylor et al., 2012). Aside from their traditional roles, some NGOs serve important information clearinghouse roles regarding adaptation (e.g., the Pew Center for Global Climate Change or the virtual Adaptation Network [http://adaptationnetwork.org]). Others have emerged as active partners in adaptation, such as the Center for Clean Air Policy (CCAP), CAKE and ICLEI Local Governments for Sustainability. CCAP is working with nine U.S. cities (and one Canadian city, Toronto) in its Urban Leaders Adaptation Initiative to help operationalize key steps in the local adaptation process (Lowe et al., 2009). ICLEI, a non-profit network of local government members, provides web-based information in support of local sustainability efforts using customized tools and case studies on assessing climate resilience and climate change adaptation. With a collaboration with King County, WA, ICLEI developed a procedural guidebook for local, regional, and state governments on how to begin preparing for the impacts of climate change (Center for Science in the Earth System and King County, 2007).

Most of these adaptation plans initially focus on few high risk areas and are then conducted in collaboration with locally based university researchers and consulting teams. Researchers have helped identify some of the physical and social characteristics that allow for the adoption of effective partnerships and implementation practices during events (Birkland, 1997; Pulwarty et al., 2009; IPCC, 2012; Mimura, 2012; Rodima-Taylor et al., 2012). These include the occurrence of previous strong focusing events (such as catastrophic extreme events) that generate significant public interest and the personal attention of key leaders, a social basis for cooperation including close intersectoral partnerships, and the existence of a supported collaborative framework between research and management such as RISAs, OURANOS, UKCIP, 5Cs. The successful boundary organizations:

- Perform basic and applied research on local climate dynamics impacts, and information prototypes relevant to stakeholder interests
- Support the integrated research base for operational informational and transition of new climate applications products
- Develop and maintain multi-way risk communication among research teams, member agencies, and stakeholders for developing information relevant for planning and decision making

While often initiated by interest in climate variability, these are advancing into climate change and adaptation planning support integrating the multiple timescales of climate risks (across extremes variability and trends). As has been noted, these efforts – while valuable and expanding – are as yet at too small level to meet the rapidly growing demand (USGCRP, 2009; Bierbaum et al., 2013). One recurring theme and lesson is the value of investments in

knowledge and information, including monitoring systems and early warning information systems that include clearer understanding of resources, health and livelihood impacts (Pulwarty et al., 2012).

Support for vulnerability and adaptation research, establishing adequate decision support institutions, as well as the building of the necessary capacity in science, the consulting world, and in government agencies, is still lags behind a rapidly growing need. With this in mind the development of climate extension services is leading to the development of the UN Global Framework on Climate Services.

15.2.4.3. Monitoring, Modeling, and Spatially Integrated Tools

The use of a decision support system (DSS) is a very effective means for a policy analyst or planner to compare different possible interventions. Through creating information products (reports, maps, diagrams, figures, visualizations, etc.), decision support systems provide knowledge of better choices about how socio-ecological coupled systems can achieve efficient, effective and equitable adaptation to global climate change. The complex, multi-scale, interdisciplinary nature of climate change impact on socio-ecological coupled systems has made the computer-based modeling approach a robust tool for understanding the evolving processes and the future conditions of the systems (Alter, 2004; Pyke et al., 2007). Typically with the widespread application of cellular automata and the multi-agent techniques since the 1980s, modeling of the behavior of physical, socio-economic or coupled systems has gained a new dynamic pace, and the role of the modeling approach in decision support tools has been enhanced (e.g., Epstein and Axtell, 1996; Wolfram, 2002).

Recent years have seen integration of monitoring systems and/or modeling systems with the techniques of geographical information systems, remote sensing and global positioning systems and “discussion support” or a dynamic dialogue between researchers and practitioners. As a result, much more powerful, process-visual and spatially implicit decision support systems have been developed. One example of this kind is the development of the Invasive Species Forecasting System (ISFS) (Stohlgren et al., 2005), which, through combining USGS science and NASA Earth observations with software engineering and high-performance computing expertise, is capable of providing regional-scale assessments of invasive species patterns and vulnerable habitats. In the Yellow River, the second largest drainage basin of China, the drying up of the channel near the mouth of the river in low-flow seasons forced governments to develop a basin-scale decision support system (Li and Li, 2009). Numerous such applications have also been made in the management of water quality, air quality, land use, crop production, and more (e.g., Jamiesona and Fedra, 1996a,b; Huang et al., 1998; Gimblett, 2002; Qin et al., 2008).

15.2.4.4. Decision Making Tools

Adaptation decision making can be kept informed by various tools, which are developed generally in ‘top-down’ and ‘bottom-up’ forms. The *top-down* tools normally downscale simulated climate scenarios to a regional level and then adopt expert opinions, apply multi-criteria optimization methods, or perform cost-effectiveness or cost-benefit analyses to assess impacts so as to identify most feasible adaptation measures (Carter et al., 1994; IPCC-TGICA, 2007; Adger et al., 2009a,b).

In the *bottom-up* approach, affected actors make their own impacts transparent and decisions at different levels on adaptive options, and the society consisting of all the stakeholders itself organizes social and institutional activities in the light of actions and interactions among all the stakeholders. Advances in stakeholder participatory methods, cellular automata and multi-agent modeling techniques have significantly enhanced the development of this type of decision making tool in recent years (Epstein and Axtell, 1996; Wolfram, 2002; Kaner et al., 2007).

The central difference between the top-down and bottom-up based tools lies in the fact that the former focuses largely on the behavior of a system as an entity, while the latter concerns mainly the roles of actors in the system. As a result, top-down based tools may yield adaptation options that may or cannot be accepted by most individuals, while bottom-up based tools may select adaptation options acceptable to most individuals but not-effective for significantly minimizing the impacts to the whole system. There is no single tool that suits all circumstances of

adaptation decision making, although information development tools such as CRiSTAL help to coordinate diver information on vulnerability and risk, and the specification of the problem and the available 'inputs' to the decision process may provide a choice of a suitable tool (Gimblett, 2002). IPCC (2012) notes the distinct differences in problem orientation and solution space depending on whether an adaptation plan commences with a climate modeling outputs-based versus that of a risk and vulnerability-based framework.

15.2.4.5. Communication Tools

Communication is a major component of social learning process and effectively exchanging and sharing information about climate change related risks and effects of adaptation measures is crucial to the identification of a right adaptation pathway out of multiple possibilities. A wide range of communication tools are being employed to carry out multi-way participatory dialogues among information developers (e.g. scientists, trainers, project implementers, government agencies, etc.) and the receivers who in turn also influence the nature of information being produced. (e.g. community members, household heads, school children, groups at risks, government regulators, etc.). They include brochures, bulletins, posters, magazines, policy briefs, desktop presentations, articles, drama, role-playing, music, group discussions, training of trainers, videos, TV and radio broadcasts, internet, and many more. While all these tools are effective in communicating risks, some of them are more cost-effective and complex than others, and some reach a wider audience than others. At the local level, interactive communication strategies such as theater, role-playing, music, and group discussions where community members are involved in debating climate risks and possible solutions to cope with climate change exert a positive effect on communities' behavior and practices, while reports, concept notes, brochures, magazines, presentations and workshops are more effective with policy makers at local and national levels. At country/regional level, nevertheless, broad dissemination channels such as TV, radio and internet broadcast, high-level summits, etc. have been effective in catering a wider range of stakeholders and creating widespread awareness as demonstrated in Advancing Capacity for Climate Change Adaptation (ACCCA) project (http://www.acccaproject.org/), UK Climate Impacts Program (UKCIP) (Pringle, 2011) and the special report of IPCC, 2012.

In addition to these commonly applied tools, innovative ways of communicating which can effectively inform the process of climate change adaptation planning and implementation are being employed. These include learning-by-doing, hands-on exercises, and training of trainers that use practical and creative cases. This is reflected particularly by the IPCC Fourth Assessment Report (IPCC, 2007), ACCCA project (http://www.acccaproject.org/), UKCIP (Pringle, 2011), the first U.S. National Assessment of the Potential Consequences of Climate Variability and Change, and the U.S. Climate Change Science Program Synthesis and 2013 National Climate Assessment products.

To assist the syntheses, a variety of rule- or matrix-based methods has been applied for screening adaptation options. For example, the Adaptation Decision Matrix uses subjective scoring to compare the relative cost-effectiveness of alternative adaptation measures (Benioff and Warren, 1996), while the RamCo (Rapid Assessment Module for Coastal Zones) system uses a series of structured questions for a decision matrix to illustrate adaptive opportunities for coastal zone management (Research Institute for Knowledge Systems, 2012). For generating visualizations and customized reports, greater emphasis on user interaction, sensitivity analysis and capabilities has been placed in recent years (Sarewitz et al., 2000; Sarewitz, 2004). Furthermore, multi-criterion and multi-actor participatory approaches that allow users to consider alternative adaptation strategies and evaluate tradeoffs have also been deployed, typically in the development of tools for environmental assessment and management (TEAM) (Julius and Scheraga, 2000).

15.2.4.6. Insurance and Social Safety

Insurance allows people and households to recover quickly and encourages adoption of new techniques so as to increase assets in a short period. These market-based arrangements have immense potential by allowing households and individuals to take advantage of the financial products offered by insurance companies and banks. Throughout the world, crop insurance and risk-pooling have allowed national economies, communities and individuals to develop the full potential of their agricultural sector by transferring weather-related risks away from the farmer.

Informal arrangements have existed for a long time, and still constitute the main source of risk management for the majority of the world's population. In the absence of (or with incomplete) market institutions and public support, individual households respond to risk by protecting themselves through informal and personal arrangements. Access to savings instruments and credit can also be facilitated. When these types of microfinance are properly provided, such as part of a well-managed and targeted intervention, it allows these households to increase their assets, improve their ability to alleviate risk and reduce their reliance on money lenders (Chu and Gupta, 1998; Holzmann and Jorgensen, 2000; Townsend, 2006).

Crop insurance will likely play a greater role in the developing world in absorbing shocks as climate-change related disasters become increasingly problematic for agricultural production. A project in Ethiopia provides a promising model. Oxfam America (http://www.oxfamamerica.org/)has developed a risk management framework to enable poor farmers in Ethiopia to strengthen their food and income security through a combination of improved resource management (risk reduction), microcredit ("smart" risk taking), risk transfer (insurance), and risk reserves (savings). This project—The Horn of Africa Risk Transfer for Adaptation (HARITA)—was initiated in 2007 and brings together Ethiopian farmers, local insurers and international re-insurers, relief societies, credit and savings institutions, local government agencies, and a local agricultural research organization. The project enables Ethiopia's poorest farmers to pay for insurance with their own labor. Meanwhile, the governments of Malawi and India have initiated pilot projects with national smallholder farmers associations that have pioneered rainfall insurance schemes to ensure payouts when rain falls below a crop-specific rainfall index. Such risk-pooling efforts, where premiums are low since they are collected only to insure immediate livelihood recovery rather than full asset losses, are also being tested at the regional-scale in the Caribbean. Index insurance has been recently introduced to overcome obstacles to traditional agricultural and disaster insurance markets. If the rainfall amount is below the threshold, then the insurance pays out. Of particular note is the Caribbean Catastrophe Risk Insurance Facility (CCRIF), the world's first index-based parametric insurance mechanism. It is a new partnership among 16 Caribbean countries and the World Bank with support from several countries, and will be tested over the coming years (CCRIF, 2012). Despite these advances, the expansion of weather-indexed crop insurance faces key challenges especially in targeting those engaged in non-commercial marginal agriculture.

15.2.5. Bridging Planning to Implementation

For adaptation planning and implementation, a variety of tools are employed depending on the social and management context. Development and diffusion of new technologies and management practices ia another important area for adaptation efforts. Although a wide range of adaptations are possible with current technologies and management practices, development and diffusion of technologies can expand the range of adaptation possibilities by expanding opportunities or reducing costs. While effective communication is important, the research experience shows that broad societal processes that create dynamic pressures and unsafe conditions are not easy to change, yet are fundamental to human vulnerability. More challenging is an understanding the socialization of lessons learned by particular individuals and organizations through their own, direct trial and error experiences. The mismatch between the current structure and operational culture of municipal planning institutions and the need for multidimensional collaboration in adaptation is reported as a planning and implementation barriers in both developing and developed countries.

Several studies have identified the characteristics of pre-decisional practices in implementation that lead to effective practice over the long-term (Fischhoff, 2009, IPCC, 2012). These include: 1) understanding of the goals, objectives, and constraints of communities in the target system; 2) mapping practical pathways to different outcomes carried out as joint problem definition and fact-finding strategies among research, extension and farmer communities; 3) bringing the delivery persons (e.g. extension personnel, research community etc.) to an understanding of what has to be done to translate current information into usable information; 4) interacting with actual and potential users to better understand informational needs, desired formats of information, and timeliness of delivery; 5) assessing impediments and opportunities to the flow of information including issues of credibility, legitimacy, compatibility (appropriate scale, content, match with existing practice) and acceptability; and 6) relying on existing stakeholders' networks and organizations to disseminate and assess climate information and forecasts.

15.3. Capabilities for Adaptation Planning and Implementation

15.3.1. Institutional Arrangements: Public- and Private-Sector Stakeholders and Priorities

While there is growing recognition that adaptation planning is essential (Ayers and Huq, 2009; Wilbanks and Kates, 2010; Ford et al., 2011), attempts at implementation have increased appreciation of the magnitude of the institutional challenges of linking adaptation planning and implementation including the problems of multi-scale coordination and support among national, state (provincial), and municipal governments to foster adaptation planning at the local level. Several studies, including municipalities in Denmark (Vammen Larsen et al., 2012), local adaptation in Florida (Mozumder et al., 2011), local governments in Australia (Doran, 2011; Gero et al., 2012; Municipal Association of Victoria (MAV), 2011), and in Sweden (Glaas et al., 2010; Storbjörk, 2007) illustrate the difficulties in creating efficient interdisciplinary integrated approaches in adaptation planning and implementation. One of the most significant challenges lies in introduce changes to the national and subnational institutional landscape in order to foster adaptation planning. Institutions are comprised of formal rules and informal codes of behavior that shape expectations and guide interactions (Ostrom, 1990). Adaptation planning follows formal institutions associated with regulations, policies, and standards created and enforced by government actors but also requires the participation of informal institutions through interactions among stakeholders according to cultural, social, and political conditions in societies (Moser and Satterthwaite, 2008; Carmin et al., 2012). Chapter 14 describes the importance of these institutional frameworks for adaptation. This section assesses the extent to which the international literature has addressed the issue of institutional arrangements fostering adaptation planning, what role different organizations (public, private, and social) and stakeholders in those arrangements have played, and what lessons can be learned from these experiences.

15.3.1.1. Institutional Capacity of National and Local Governments

The review of the broad international literature suggests the development of institutional arrangements for adaptation planning is at an early stage both at the national and at the subnational level (Carmin et al., 2012; Gero, 2012; Glaas et al., 2010; Gupta et al., 2010; Rodima-Taylor et al., 2012; Tompkins et al., 2010). Huntjens et al. (2012) compare adaptation to climate change in the Netherlands, Australia, and South Africa in an effort to identify strategies that move from individual impacts to more holistic approaches increasing the adaptive capacity of the system. Tompkins et al. (2010) and other studies of climate change adaptation in the United Kingdom consider a broad range of adaptation actions, from small adjustments to creating deeper systematic change in public and private organizations. These authors argue that the transition to deeper systematic changes could eventually result from a set of simultaneous changes (changes in technology, user practices, regulation, industrial networks, infrastructure, symbolic meanings, and culture). Some of these elements are part of the institutional adjustments discussed above. As with other studies, in the context of adaptation planning, find there is no evidence to show that adaptation planners are deliberately working towards transitions and with little real evidence of climate change adaptation initiatives trickling down to local government level.

Climate adaptation is uniquely linked to location, and it is often a responsibility of local governments, stakeholders, and communities (Mattews et al., 2012). The importance of multilevel institutional arrangements is increasingly cited (Corfee-Morlot et al., 2009; Gero et al., 2012; Storbjork, 2007; Vammen Larsen et al., 2012; Wilson 2006). Carmin et al. (2012) describe the importance of developing regulations, policies, and codes to support the institutionalization of local climate actions. Roberts (2010) describes the difficulties of operationalizing development in Durban, where some departments were able to mainstream adaptation activities into their ongoing work while others did not have that capacity. Vammen Larsen et al.'s (2012) study in Denmark reports the rapid incorporation of climate change in the Strategic Environmental Assessments (SEA) of the new municipal plans prepared by local governments in that country in 2009. The study showed that the current structure of the municipal organization is made of different professional silos with their own internal norms, cultures and procedures that may hinder horizontal coordination across professional sectors and departments. The study showed also there are few national requirements or guidelines to help local governments integrate climate change into spatial planning. The lack of national guidelines is also reported in Norway (Amundsen et al., 2010) in Sweden (Glaas et al., 2011;

Storbjork, 2007) and in Australia (Gero et al., 2012; Municipal Association of Victoria (MAV), 2011). Vammen Larsen et al. (2012) stress that climate change does not posses clear institutional characteristics as a municipal professional area. Rather, it is viewed as a void with no clear rules and norms according to which politics is to be conducted and policy measures agreed upon. While the institutionalization of climate change integration has begun, it is unknown whether the municipalities will be successful in developing the governing capacity needed.

15.3.1.2. Role of Spatial Planning

The review of the literature above suggests that planning has been widely considered in adaptation, but perhaps not enough attention has been given to study the capacity of current planning institutions. This is required in order to move toward a balance of top-down and bottom-up strategies in adaptation. Planning is considered a societal tool to create order among activities and interests driving growth in societies, to reduce conflicts among them, and to seek the well-being of their inhabitants (Blair, 1973). Some of the literature is beginning to focus on the capacity of planning to address adaptation to climate change. Juhola and Westerhoff (2011) stress the transition of adaptation from being first considered a matter of relevance only to the environmental sector, to a development challenge that will require the participation and cooperation of a multitude of sectors to avoid potential conflicts. Sanchez-Sanchez-Rodriguez (2012) highlights the role and limitations of planning in the construction of operational approaches to adaptation, particularly in urban areas of low-income and middle-income countries. He questions if planning institutions have the vision, capacity, and flexibility to update themselves, and to guide future urban growth in order to meet the challenges facing to their future. This is an important question given the expectations that planning will be able to create order and balance in adaptation to climate change, and in light of the reticence of planning institutions to change their operations and structures.

Mozumder et al. (2011) study on the role of experts and decision-makers building adaptation to climate change in the Florida Keys reveals they are currently operating with limited information, and lack a formal institutional framework necessary to shape and execute adaptation measures. Other studies suggest there have been few changes in forecasts, plans, design criteria, investment decisions, budgets or staffing patterns in response to climate risks (Repetto, 2008; Berrang-Ford et al., 2011).

Biesbroek et al. (2009) considers that climate change could also lead to changes in the traditional administrative structures to which spatial planners are accustomed. Other literature emphasizes the role of spatial planning as a switchboard for adaptation and sustainable development change (Füssel, 2007; Hallegatte, 2009; Preston et al., 2011). Biesbroek et al. (2009) stress spatial planning coordinates the different relevant socio-economic objectives and desires, and shaping spatial developments in a long-term perspective. However, they recognize it is becoming more and more a pragmatic challenge for spatial planners to include climate change as an important consideration in the planning process, especially in the context of sustainable development. Bulkeley (2006) concludes that given the complexity, uncertainties and scale of the climate change issue, spatial planning might play a key role in facilitating the development of both adaptation and mitigation strategies with a spatial component. However, not enough attention has been provided yet to the institutional arrangements needed to enable adaptation through spatial planning.

The review of the international literature discussed above identifies two major trends: First there is the assumption that current of planning structures and operational cultures will be able to meet the needs of adaptation on different scales (regional, national, and subnational); and second, there are studies that document the shortcomings, challenges and opportunities of planning as a societal process that is needed to create and implement adaptation, bringing more attention to the institutional changes required to build efficient responses to climate change.

Some literature on adaptation has suggested the importance of considering adaptation planning as a learning process (Glaas et al., 2010; Hinkel et al., 2009; Hofmann et al., 2011) likely to require regular revisiting of development policies, plans and projects as climate and socioeconomic conditions change and adaptation plans need revision. Holden (2008) suggests that social learning is a relevant but under-investigated feature of planning and a critical part in the adaptation of innovations but there are few analytical tools to assess how and when learning is taking place, and amongst different professional and public communities. Considering adaptation planning a social learning

process would allow for periodical adjustments in order to reduce the uncertainty of the impacts of climate change and societal needs to cope with them. This is relevant in light of the need to develop new tools to cope and adapt with the impacts of climate change (Frommer, 2009). But it will require major efforts in multilevel and cross-sectoral collaboration, as well as a broader attention by scholars and practitioners to develop a better understanding of this process.

Important learning tools in adaptation planning are monitoring, evaluation and feedback. Although some recognize the importance of evaluation in adaptation, this topic is under-researched and requires significant work to go beyond the simple evaluation criteria that have been developed to date (Doria et al., 2009). Preston et al. (2009) suggest the institutional arrangements for the evaluation of adaptation processes are still in their developmental infancy. Monitoring and evaluation are often advocated within adaptation decision making frameworks, but methods for undertaking such work are rarely articulated, and adaptation plans frequently fail to acknowledge the importance of core design principles for adaptation policies and measures such as efficacy, efficiency and equity. Reidsma et al. (2010) and IPCC SREX (2012) argue that in order to assess the effectiveness of adaptation strategies, frameworks should not start from the modeling perspective, but from the stakeholders' perspective.

Adger and Barnett (2009) argue that metrics used to determine the goals of adaptation, the measures of its success and the trade-offs involved, can be understood only in terms of the social context in which adaptation takes place. Communities value things differently, and this must be taken into account if adaptation is to be effective, efficient, legitimate, and equitable (Barnett and Campbell, 2009). Arnell (2010) highlights the importance of context in the analysis and evaluation of adaptation. His review shows that local circumstances significantly affect what adaptation options are considered feasible, what information is likely to be used, what assessment techniques are adopted, and, crucially, how adaptation decisions are actually made. This work indicates that it could be difficult to make generalized assessments about the contribution of adaptation to managing the risks posed by climate change, and to construct generalized models of the adaptation process.

By the same token, Engle (2011) calls attention to the limited effort to evaluate adaptive capacity across vulnerability and resilience frameworks, and to improve the understanding of adaptive capacity dynamics. For him, it is important to identify what builds adaptive capacity and what functions as limits and barriers to adaptation. Hinkel (2010) questions the use of vulnerability as a concept to increasing awareness of the importance of adaptation, to guide the allocation of adaptation funds, monitoring of adaptation policy, and conducting scientific research. He finds it misleading to speak of measuring vulnerability as it raises false expectations.

Providing spatial planning a bigger role in institutionalizing adaptation planning at the local level requires the participation and cooperation of a multitude of sectors to avoid potential conflicts (Juhola and Westerhoff, 2011). Anguelovski and Carmin (2011) highlights the ways in which public, private, and civil society actors and institutions articulate climate goals, exercise influence and authority, and manage urban climate planning and implementation processes. They document that urban areas tend to formalize and institutionalize their work through the establishment of dedicated climate units, either within a relevant department or as a separate and cross-cutting office. However, they recognize few local governments have had the resources and know-how to institutionalize adaptation to climate change.

Koch et al. (2007) stress the gap in understanding and evaluating how institutional networks operate. Their research results in South Africa show that few institutions fully understand the implications of adaptation, and their roles and responsibilities have not yet been properly defined. They suggest constraints relating to capacity, lack of awareness and poor information flow need to be addressed. Adaptation challenges the hierarchical manner in which government works, and a more collaborative approach to climate change adaptation is needed. These and other recent contributions in the literature (Adger et al., 2009b; Preston et al., 2009; Tompkins et al., 2010; Wolf et al., 2010) move the discussion of adaptation planning to climate change to a better understanding of the elements needed to operationalize this concept, building responses to present and future climate impacts.

15.3.1.3. Institutional Arrangements and Disaster Risk Management

The divide between the Disaster Risk Management (DRM) and the Climate Change Adaptation (CCA) communities at the national, subnational, and local level is evident in a large number of countries (Birkmann and Teichman, 2010; Falaleeva et al., 2011; Schipper and Pelling, 2006; World Bank, 2010). International pressure to draft separate disaster and adaptation strategies and policies has now become enshrined in divergent laws, creating further obstacles to institutional integration of DRM and CCA. The convergence of adaptation planning and disaster risk management offers opportunities to more efficent use of resources and effective and coherent short and long-term responses to hidrometeorological events and climate change (IPCC, 2012). It can enhance attention to climate change adaptation and awarness of the need of short, medium, and long-term strategies to build resilient and sustainable communities. This convergence helps decision-makers build a better understanding of present and future risks and their consequences for development. One of the problems they face is the short-term horizons of local plans compared with the long-term implications of vulnerability and climate change.

The convergence of DRM and CCA need building capabilities in institutions to recognize and better understand vulnerabilities to hydrometeorological and climate change simultaneously (Agrawal and Perrin, 2008; Agrawal 2010). Some early examples in this direction are ecouraging. In a study of current and future city-wide flood risks to Ho Chi Minh City in Vietnam, Storch and Downes (2011) connects spatial planning scenarios linking urban growth and climate change (sea-level rise scenarios) in order to explore the main driving forces for future risks. There is a growing interest connecting initiatives for disaster risk management and climate change adaptation planning (Bierkman, 2010; Rosenzweig and Solecki, 2010; Carmin et al., 2012). The World Bank prepared guidelines to connect disaster risk management, poverty reduction and climate change adaptation and emphasize the role of planning and participatory approaches (World Bank, 2010). Mathew et al. (2012) describes the benefits of defining adaptation options in consultation with local authorities in a study on climatic hazards in Kochi, India. Frazier et al. (2010) explore stakeholder participation in the context of coastal hazards concluding that adaptation planning tends to be more difficult in areas that lack recent disaster experience.

Some countries expand the divide between DRM and CCA. For instance, Mexico published a new National Climate Change Law in 2012, but instead of integrating DRM as one of its key components, it published simustaneously a new Disaster Risk Management Law. In general little progress has been made integrating DRM and CCA at the national, subnational, and local level. The Birkmann and Teichman (2010) study on the U.K. Germany, and Fiji found that little action has been taken at the national level to establish working relationships between adaptation planning and DRM. The convergence of DRM and CCA require new institutional arrangements, particularly in terms of legislation, operational and management structures, working agendas, and time horizons (Birkmann and Teichman, 2010; Falaleeva et al., 2011; Schipper and Pelling, 2006).

15.3.1.4. Enhancing Institutional Capacity

Two key issues emerge in the literature as essential for enhacing the institutional capacity of adaptation: multilevel governance and cross-sectoral frameworks. Although these two issues interact dynamically in adaptation planning and implementation, they have different connotations and require specific actions to enhance and strengthen their practices.

15.3.2. Knowledge Development and Sharing

Scientists and managers across agencies and management systems would benefit from greater sharing of data, models, and experiences in climate change adaptation (West et al., 2009). Indigenous observations and interpretations of meteorological phenomena have guided seasonal and inter-annual activities of local communities for millennia. However the number of documents published about knowledge development and sharing is still limited. The available documents deal mainly with general principles rather than practical applications. The current section outlines the main relevant issues surrounding knowledge development and sharing in adaptation to climate change.

15.3.2.1. Science and Technologies for Observation, Monitoring, and Prediction

Development and diffusion of new technologies and management practices will be critical to many adaptation efforts. The role of technology is not so much to make adaptation possible-a wide range of adaptations are possible with current technologies and management practices-but to expand the range of adaptation possibilities by expanding opportunities or reducing costs (Smith et al., 2009). The status quo generally requires no new capital costs and may be more profitable in the short term than developing more climate-resilient technologies (Yang et al., 2007). Several researches indicated the autonomous adaptation to climate change of many animals and plants (Mastrandrea et al., 2010; Tingley et al., 2009).

15.3.2.2. Early Warning Information Systems

Monitoring and early warning systems (EWS) have long-played important roles in helping in adjustment, and adaptation especially on the local scale. The disaster research community has shown that successful warnings of impending events are those that are complemented by information on the risks actually posed by the hazards as well as the potential strategies and pathways to mitigate the damage in the particular context in which they arise (Drabek, 1999; UNISDR, 2006). While current science and technology do not resolve the uncertainties in modeling, and in the response of ecosystems to climate change and management interventions at levels needed for probabilistic early warning, the need for precise climate information is often overstated (Smith et al, 2009). Local level early warnings based on traditional knowledge (e.g. water turning a different color, winds shifting) are frequently used. The use of radios, megaphones, and cell phones are also used at the local level to warn. Countries that have not developed such systems, even in part, to develop and inform strategic response options often illustrate a broader lack of institutional flexibility and preparedness and thus higher vulnerability. Given the links between near term and long-term climate variability and change, the early warning construct is, of necessity, being applied to more extended timescales.

The impacts of climate change will be most strongly felt by resource insecure populations, who are more vulnerable to changes in the distribution and magnitude of extreme weather events, as these affect crops, disease outbreaks and soil and water quality. The use of climate data analyses and projections in early warning and information systems is an important and established mechanism to mitigate the effects of natural disasters (Pulwarty and Verdin, 2013). An early warning information system involves much more than developing and disseminating a forecast.

The long-standing experience with climate extremes and variability offers many usable lessons. The U.S. National Integrated Drought Information System offers an end to end system in which monitoring and forecasting, risk assessment and communication are integrated, but as importantly interagency cross-coordination is a goal and is are increasingly embedded with states and local communities (Pulwarty and Verdin, 2013; Bierbaum et al., 2013) The USAID's Famine Early Warning System Network (FEWSNet), for instance, integrates seasonal climate forecasts into 3- and 6-month food security outlooks, and it has developed 10-20 year climate projections for food insecure regions of Africa. FEWSNet has also created livelihood zone maps, profiles, and baselines for some of the most food insecure countries of Sub-Saharan Africa, Central Asia, Central America, and the Caribbean. These maps and profiles describe areas in terms of food production, income generation, and market opportunities, and they make distinctions between different wealth groups and their respective coping capacities for dealing with shocks, including drought. These are valuable tools that could help countries develop adaptation strategies to cope with the predicted increases in drought frequency and severity.

The EWSs are often utilized for disaster management by traditional media (radio, TV). However, to ensure the collection and dissemination of information and delivery of early warnings, the EWSs need new Information and Communication Technologies (ICT) for analysing and processing information, and providing automated alerts to vulnerable populations (Karanasios, 2011). Local coping strategies are an important element of planning for adaptation, and ICTs can be used in a number of productive ways, particularly by leveraging existing ICT successes in developing countries such as telecentres and mobile phones, as well as by introducing emergent ICTs in

conjunction with existing sectoral policies, planning and budgeting (UNFCCC, 2007).Insurance and and the basis for finacial services mechanisms are discussed in detail in Chaptet 10.

15.3.2.3. Science and Technologies for Vulnerability Assessment, and Adaptation Planning and Implementation

Effective collaboration and linkages between managers and scientists offer a variety of opportunities for adaptation implementation. First, resource scientists have monitoring data and research results that are often under-used. Second, monitoring efforts could be conducted with specific objectives in mind to increase usefulness for managers. Finally, scientists can support management by targeting their research. All of these are opportunities for interactions between scientists and managers that provide information relevant to major management challenges (Füssel, 2007).

Adaptation action, such as changes in crops and crop varieties, improved water management and irrigation systems, and changes in planting schedules and tillage practices, can limit negative effects and take advantage of beneficial changes in climate (Yang et al., 2007). The adaptation part of this is based on a science-policy collaborative exchange that has operated in various forms for about a decade, and has successfully co-produced scientific assessments (Corfee-Morlot et al., 2011).

ICTs can help strengthen the physical preparedness of livelihood systems for climate change-related events. These can contribute to design of defences and determination of their optimal location, and make the livelihood system more robust. As an example geographic information system (GIS) technology was applied to foster the ability of the community to deal with climate change hazards and trends in the Philippines (IAPAD, 2010) and form modelling processes of climate change adaptation which which supports regional stakeholders to develop better protection of key spaces in the landscape (Bardsley and Sweeney, 2010). Visualization of sea level rise and climate change damage in Delta, British Columbia, and subsequent illustrations of options for adaptation, has led to increased awareness of long-term risks and response challenges between practitioners in this community, as well as by local government and the public (Shaw et al. 2009).

By sharing observations and reflections through ICT tools, users foster new ways of assimilating or translating information, which can be shared through wider networks, and then influence action, enabling new experiments/practices to take place. This generation of new and broader learning cycles will in turn strengthen systematic resilience (Ospina and Heeks, 2010). Karanasios (2011) outlines the range of new and emergent ICTs (e.g. wireless broadband, sensor networks, GIS and Web-based tools) being applied to climate change issues, and investigates their use in developing countries.

15.3.2.4. Science and Technologies for Individual Sectors

The adoption of advanced technologies greatly facilitated agricultural development. New varieties and new fertilizers, pesticides, and agricultural techniques have been actively adopted (Yang et al., 2007). In the sector of logistics, on a global scale, most sea ports are in the beginning stages of considering adaptation to climate change. There is an opportunity for the scientific community to engage with this sector to create the knowledge base needed to understand and improve resilience and efficiency in the coming century (Becker et al., 2011). The European Spatial Planning Adapting to Climate Events Project (ESPACE) asserts that while adaptation presents a variety of new issues for urban planning, it can be an opportunity for good planning to thrive. It is further argued that good planning can positively contribute to adaptive efforts if it works within its means, and correctly uses the tools available to it such as adaptation through infrastructure and design (porous surfacing, green roofs, etc.) (ESPACE, 2008). The linkage between disaster risk reduction (DRR) and adaptation can help communities to build resilience and live with change.

15.3.2.5. Technology Development, Transfer, and Diffusion

Technology is essential for adaptation to climate change, and access to technologies is an important component of a society's adaptive capacity. In some settings, adaptation could be made more effective and efficient by technologies such as new crop varieties tolerant of changed conditions and more efficient water treatment. However, successful deployment of technology is dependent on local social and institutional contexts. Technologies will therefore be more effective when used within multiple adaptation measures that integrate different sectors and social, institutional, and infrastructural dimensions (Rawlani and Sovacool, 2011).

Technologies related to information collection and diffusion are particularly important for adaptation, including technologies for data collection and information dissemination during extreme events and emergencies. Despite remaining uncertainties, technologies to project climate changes, and identify potential impacts and vulnerabilities are frequently seen as precursors to successful adaptation planning. Developing countries require enhanced access to improved climate models, but also adaptation planning tools that focus on robustness in the face of uncertainty (Dessai et al., 2009).

Technology choices can both reduce and exacerbate risk (Jonkman et al., 2010). For example, technologies can strengthen physical infrastructure, such as bridges and buildings, so that they can withstand more extreme hazards. However, relatively centralized high-technology systems can increase efficiency under normal conditions but risk cascading malfunctions in the event of emergencies. In some circumstances, technologies to reduce short-term risk and vulnerability can contribute to increased future vulnerability to larger extreme events (Etkin, 1999; Moser, 2010). This was seen in the impacts of Hurricane Katrina on New Orleans, where a flood defense system enabling construction in a floodplain was subject to catastrophic failure in the face of a particularly large extreme event (Freudenburg et al., 2008; Link, 2010).

Planning for physical infrastructure intended to last decades should account for potential changes in associated social conditions, such as land use, transport, and water and sanitation requirements, in order to avoid maladaptation. Technology development and transfer should promote flexible solutions, for example multiple, smaller dams that can resolve local as well as more distant needs. This has been expressed in Thailand's Sufficiency Economy approach, where local development is judged against contributions to local, national and international wealth generation (UNDP, 2007).

International efforts for technology transfer have been concentrated in the UNFCCC framework's five themes: technology needs and needs assessments, technology information, enabling environments, capacity building, and mechanisms for technology transfer. A key project is developing a technology transfer clearinghouse called TT:CLEAR, and establishing a Technology Centre and Network (UNFCCC, 2012). However, successful technology transfer requires not only exchange of technological solutions, but also strengthening policy and regulatory environments, and capacities to absorb, employ and improve appropriate technologies. In both developed and developing countries, multilateral institutions can support collaboration which engages private interests in regulatory planning and possibly activities, particularly if ongoing funding is expected (Tessa and Kurukulasuriya, 2010).

15.3.2.6. Education and Training

Developing general guidance on potential climate change impacts, vulnerability, and adaptation helps the promotion of flexible approaches to adaptation planning and implementation. It means investing in climate science extension personnel including translators, who could work in partnership with managers and planners to translate the projections of climate models, understand potential impacts, and help design adaptation responses. These individuals would also function as outreach staff who could explain to the public what climate change might mean to long-standing opportunities or management goals (West et al., 2009).

The farmers in Northeast China learn to adapt to climate change through experience and self-judgment, but also, and importantly, from neighbors' practices and scientific demonstrations. Scientists played a supporting role by discerning long-term climate trends, predicting future scenarios, and recommending development blueprints and

technologies (Yang et al., 2007). In the built environment sector of Australia, (Lyth et al., 2007) recommend that education about and for climate change adaptation in accredited courses be addressed in an integrated way with education about and for climate change mitigation in Australia. Programs for Master and Ph.D degreees with specific applications for climate change impacts, vulnerability, adaptation, and capacity assessment have been established in many universities such as United Nations Univerwsity and The University of the West Indies.

15.3.2.7. Local and Traditional Knowledge

Local and traditional knowledge is gained by longtime recognition and adjustment to adverse events. The value of local knowledge was given primacy, be it to complement scientific climate data, to provide insights about and for climate change adaptation, or as a source of community-based environmental monitoring (Newsham and Thomas, 2011; Nakashima et al, 2012).

Rural populations have an considerable capacity to adapt to a range of climatic and non-climatic risks. However, this capacity does have limits that can be exceeded, especially when climate-related stresses are superimposed on other forces that give rise to vulnerability. Whether that threshold is exceeded is strongly influenced by the role that higher-level actors such as governments choose to play in providing adaptation assistance and capacity-building (McLeman et al., 2008). Local agro-ecological knowledge in North Central Namibia has provided farmers with resilience in the face of a highly variable, and hence uncertain, climate for perhaps hundreds of years (Newsham and Thomas, 2011). Most of the farmers in the Mekong river delta had applied them personally during major flood events in the past such as lifting the ground floor level, moving important items to upper floors, sending the children to day care centers, and selling livestock in case of very large floods (Birkmann, 2011). A summary of the integration of indigenous peoples' knowledge and observations of environmental processes in developing collective responses to climate change in Africa, Australia, small islands in the Asia-Pacific region, and the Arctic Ocean concludes that knowledge co-development helps to realize the purpose of developing climate change mitigation, adaptation strategies and actions (Green and Raygorodetsky, 2010).

Adaptation plans in developing countries tend to be stakeholder-driven, and implemented at the local level, where there is ample opportunity to include capacity-building as part of the adaptation plan (Berrang-Ford et al., 2011; Ford et al., 2011). Some recent climate community-scale adaptation plans as well as local adaptation methods have increased adaptive capacity by re-introducing indigenous varieties of crops that are selected by local farmers to be more resilient to changing conditions, and by initiating subsistence farming of a broad variety of vegetables in regions where local economies are dependent on the success of a few to sometimes one cereal crop (Deressa et al., 2009; Ensor and Berger, 2009).

15.3.3. Learning and Capacity-Building

15.3.3.1. Perception of Climate Change and Adaptation

In regions where there is awareness of climate change, people tend to have greater adaptive capacity and are more proactive in adaptation responses (Di Falco and Veronesi, 2011). However, there are still cases where there are gaps in knowledge between projected and perceived risks, as well as the degree of uncertainty. Individuals in flood-prone areas, in educated, affluent regions as well as developing countries, commonly miscalculate the degree of flood risk (Lata and Nunn, 2012; Ludy and Kondolf, 2012; Bell and Tobin, 2007). In some cases, people are aware of the dangers from flooding, riverbank erosion, etc., but do not necessarily attribute these risks to possible manifestations of climate change or the need to adapt to changing hazard frequency (Lata and Nunn, 2012). Additionally, there have been very few documented changes in forecasts, plans, design criteria, investment decisions, budgets or staffing patterns in response to climate risks (Berrang-Ford et al., 2011; Repetto, 2008). Because there is uncertainty about the future climate, new decision making tools need to be developed to cope with the impacts (Frommer, 2009). Adaptation in addition to mitigation is growing in mainstream policy efforts in response to climate change (Preston et al., 2009). However, there is a significant gap between adaptation recommendations and planning, and actual implementation efforts (Berrang-Ford et al., 2011; Repetto, 2008).

Building capacity to respond to change, whether expected or unexpected, creates resilience in communities to cope in the face of uncertainties in climate change projections. Because in both developed and developing countries, climate change adaptation is not viewed as a high priority because of more immediate needs that are based on short-term economic welfare (Coles and Scott, 2009). In developing countries there are also additional challenges in obtaining basic human requirements and to address human health. People in developing countries are particularly vulnerable to climate change and more directly impacted by climatic hazards, in part because their economies tend to be more natural resource-dependent (Nath and Behera, 2010; Reid et al, 2010; Handmer, 2009). Greater exposure is often accompanied by a deficit of adaptive capacity, because poorer, less educated populations tend to have less access to information about climate risks, and fewer economic and technical resources available (Sissoko et al., 2011; Reid et al., 2010).

15.3.3.2. Balancing Mitigation and Adaptation Responses to Climate Change

Three major themes where adaptation and mitigation issues are expected to coincide are agriculture, built environment and carbon sequestration through re-vegetation. In north central Victoria, Australia, Jones et al. (2007) describe adaptation and mitigation efforts that are jointly managed by a greenhouse consortium and a catchment management authority. They conclude that when managing climate change risks, adaptation and mitigation can be integrated at the operational level. However, significant gaps in understanding the benefits of adaptation and mitigation on the local and global scales remain. Links between adaptation and mitigation can be strengthened by reduction of emissions from deforestation and forest degradation, as they contribute to conserving and restoring ecosystem service (Van Aalst et al., 2008). The Klima-Werkstatt project (Germany) has invested in climate change mitigation and adaptation by communicating the added value of climate-friendly products and services. It provides demand-oriented knowledge transfer, and develops opportunities for stakeholder participation. A long-term goal is to develop a stakeholder network that is a self-supporting structure (Frommer, 2009).

15.3.3.3. Opportunities to Improve the Communication between Science and Practice in the Creation of Decisionmaking Support Information and Tools

Decision analysis tools have been valuable as a means of informing decision-makers. Whether it is multicriteria analysis, benefit-cost analysis, or any number of other tools, part of the analytical process will always be difficult and challenging primarily because of underlying uncertainties and differing local conditions (Smith et al., 2009). Decision support systems for climate adaptation have been set up for various sectors such as water (Stakhiv and Stewart, 2010), ecosystem (Munang et al, 2010), and tourism (Scott and Lemieux, 2010). Several efforts at defining frameworks to guide decision-makers dealing explicitly with climate adaptation are a valuable start, but more practice-oriented evaluation of such tools is merited (Smith et al., 2009). Networks are useful tools to develop individual adaptation options on the local and regional scales, e.g., the KLARA-Net builds on four fields of action, as follows: ‘spatial planning + building industry + water resources management’, ‘agriculture, viniculture + forestry’, ‘tourism’, and ‘health’. Each of these fields of action is operationalized by a working group (Frommer, 2009).

15.3.3.4. Developing Localized Information for Adaptation Planning and Implementation

Community-based climate change adaptation plans have included strategies for disseminating information on climate change and raising awareness using novel and creative methods, including art and essay writing contests, public information posters, and signs on rickshaws. Community engagement offers additional opportunities to discuss climate change impacts in plans by including baseline surveys of community members, public discussions at existing village level social platforms, demonstration projects, and festivals (Mekong River Commission, 2010; Ensor and Berger, 2009). It also allows incorporation of local or traditional knowledge into climate change adaptation plans.

Conservation management of important and threatened resources can be strengthened by using local knowledge. In Kenya, local ecological knowledge about the harvesting of papyrus and the recovery time between harvests has been critical to developing sound conservation strategies (Terer et al., 2012). The local plant knowledge shared among tribal elders of the Standing Rock Lakota tribe has served as an adaptive asset that may be important for the survival of cultural practices under changing climatic conditions (Ruelle and Kassam, 2011). Additionally, indigenous knowledge has been used to predict weather and climate for generations in Malawi. Local farmers in this Sub-Saharan region of Africa rely on indigenous knowledge, and have not found conventional scientific weather predictions as useful at the local level (Kalanda-Joshua et al., 2011)

15.3.4. Preparing for Surprises: Role of Buffers

Disaster risk reduction is an important but often unrecognised and undervalued service provided by healthy ecosystems (UNISDR, 2011). The above cases suggest that under transitional climate change, due to climate variability and extreme events appear thresholds may be breached more frequently. In the face of mounting evidence of the biological and ecological consequences of climate change, and of the possibility that changes to ecosystems may in fact be rapid, large, and sometimes irreversible (i.e. there may be thresholds that, once crossed, will exacerbate coping challenges to humans), policy makers and resource managers are confronted with the need to develop ways to proceed with decision-making in the realms of both mitigation and adaptation, despite the many uncertainties associated with thresholds (Scheffer, 2009).

For instance, forest protected areas help conserve ecosystems that provide habitat, shelter, food, raw materials, genetic materials, a barrier against disasters, a stable source of resources and many other ecosystem goods and services – and thus can have an important role in helping species, people and countries adapt to climate change. Such systems continue to serve as a natural storehouse of goods and services into the future (Dudley, 2008). As part of its Climate Change Framework Strategy (World Bank, 2008), the World Bank is advocating that ecosystem-based adaptation to maintain ecosystem services and sustainable income-generating activities in the face of climate change. The Reduced Emissions from Deforestation and forest Degradation (REDD) is a major effort to produce co-benefits of reducing GHGs and ensuring livelihoods (Ezzine-de-Blas et al, 2011). Protected areas have been recognized for several decades as an essential tool for conserving biodiversity.

Guatemala's Mayan Biosphere Reserve provides employment for over 7 000 people and generates an annual income of approximately US$47 million (Poverty and Conservation Learning Group (PCLG), 2002). In Madagascar, a study of 41 reserves found that the economic rate of return of the protected area system was 54 percent, essentially from watershed protection and to a lesser extent from ecotourism (Naughton-Treveset al., 2005). Thus, protected areas provide a safety net which can be valuable in times of stress, such as extreme climate events.

In Kimbe Bay, Papua New Guinea, a network of marine protected areas were developed based on coral reef protection to help the Bay's ecosystems withstand the impacts of a warming ocean and continue to provide food and other resources to local communities (Green et al., 2009). In Samoa, mangroves are being planted as part of a larger restoration project to enhance food security and protect local communities from storm surges anticipated to increase as a result of climate change. In Myanmar, communities are replanting mangroves in the Irawaddy Delta following the destructive impact of Cyclone Nargis, which devastated life and property in the absence of mangrove forests, cleared over time for paddy cultivation (Tripartite Core Group, 2008). Mangrove restoration in Vietnam has been shown to attenuate wave height and thus reduce wave damage and erosion (Mazda et al., 1997). Sri Lanka's Muthurajawela marsh, a coastal peat bog covering some 3,100 hectares, is an important part of local flood control. Low cost behavioral actions can provide benefits within a short time. One such example, the Humbo Project, assists communities affected by ecosystem degradation including loss of biodiversity, erosion, and flooding with an opportunity to benefit from carbon markets. Farmer-managed natural regeneration has been involved in the regeneration of 2728 ha of degraded native forests in Humbo, Ethiopia (Brown et al., 2010). Benefits have included fodder and firewood in the first year, and fruit and non-timber products within three years. Indigenous communities have been using such low cost actions for generations. Highly rated adaptation options that are being implemented add climate change to already existing activities for managing climate-related and other risks. These include

integrated ecosystem and water management, integrated coastal zone management, risk-based allocation policy, risk management as basic strategy, and new institutional alliances (Füssel, 2007).

The impacts of climate change now give these approaches a renewed role as adaptation tools for a changing climate. Their importance in this respect is threefold (see Box CC-EA):

1) In supporting species to adapt to changing climate patterns and sudden climate events by providing refuges and migration corridors
2) In protecting people from sudden climatic events and reducing vulnerability to floods, droughts and other weather-induced problems
3) Indirectly, in supporting economies to adapt to climate change by reducing the costs of climate-related negative impacts.

15.4. Governing Adaptation

An assessment of the literature draws attention to the point that adaptation to climate change poses governance challenges such that arrangements inconsistent with governance principles. The role of governance is highlighted in building adaptive capacity to climate change (Engle and Lemos, 2010) and providing the connections between individuals, communities, organisations, agencies, and institutions at multiple organizational levels (Folke et al., 2005) and in articulating top-down or bottom-up perspectives which are both critical in policy formulation (Unwin and Jordan, 2008). Such organisations often draws from various knowledge systems and experiences in developing a common understanding and policies on an issue critical for cross-institutional coordination and multi-stakeholders actions. For example, mechanisms to facilitate learning processes are considered to support the management of complexity especially in cross-boundary and large scale resource systems. (Huntjens et al., 2012).

15.4.1. Factors for Adaptation Governance - Institutional, Financial, Incentives, Information Management

An assessment of the literature points out that adaptation is influenced by social factors which require having learning, cooperation and communication as part of the planning especially at the local level where the action takes place (Resilient Cities, 2011). Accountability is considered a factor which highlights a participatory process (Akompab et al., 2012). Similarly, knowledge is important for adaptation governance following the opportunity it offers for learning especially in supporting a feedback mechanism for improvement (Nilsson et al., 2012) and providing the context for adaptive governance (Bruner, 2010) in contribution to overall adaptive capacity to climate change (Preston et al., 2011). Incentives for economic growth and profitability in coping with climate change are also considered as an important factor of governance (Manuel-Navarrete et al., 2009).

Institutional dynamics is a factor of adaptation governance especially in fostering transboundary collaboration (Wilder et al., 2010). This is important in overcoming some of the adaptation barriers posed by hierarchical government structure by shifting towards a more collaborative approach following the multi-dimension and numerous state and non-state actors involved in adaptation (Koch et. al., 2007). Decentralised decision-making, open information sources, and plurality of user interests are important factors of governance emphasized in the literature for promoting multilevel institutions that are robust and able to learn (Bisaro et al., 2010; Rao, 2012). Case studies of fishing communities in northern Norway and north-west Russia showed that the adaptive capacity of local actors to respond to climate change is influenced politically beyond their immediate locality, within broader governance system (Keskitalo and Kulyasova, 2009). An instructive lesson on cost-effectiveness, sustainability, citizenship and social cohesion is taken from the UNISDR (2011) Global Assessment Report on Disaster Rick Reduction. The report notes that the central government level responsibility for disaster risk management needs to be located in a ministry or department, preferably with planning oversight and some fiscal responsibility that can provide political authority and policy coherence across sectors. Emergency management organizations can rarely play that role. The decentralization of responsibilities to local governments needs to be accompanied by a decentralization of capacities and resources – otherwise it may become an obstacle to effective DRM. Decentralization should be incremental and approaches such as twinning may facilitate capacity development, and will only be effective when it is carried out in real partnership with disaster prone households and communities and

their organizations. There are a growing number of positive examples of such partnerships. In many countries this however implies a change in the culture of public administration and the critical role of key individuals or policy entrepreneurs at every level cannot be underestimated.

15.4.2. Cross-Sector Coordination

Norman (2009) highlights the importance of intergovernmental and multidisciplinary approaches integrating science and spatial planning as an efficient approach to address those conflicts between adaptation and mitigation as discussed in 15.2.2.2. Bottom-up approaches can be particularly useful in efforts seeking to reduce social and urban vulnerability, and addressing adaptation to climate change as a process. However, adaptation to climate change requires also complementary top-down strategies through urban and state institutions (Raschky, 2008).

Linking climate change risks to systems and sectors, and the corresponding response planning and implementation actions occurring at different spatial and temporal scales, requires cross-coordination. Jurisdictional scales and mandates across sectors, and local, national and sub-national policies, constrict the potential benefits of close dependencies between institutions, institutional systems and organizational units in planning and implementation of adaptation (Dovers and Hezri, 2010). The lack of coordination in the scale of governance together with unclear division of tasks and responsibilities of actors, especially under conflicting timescales of interventions, are significant barriers to adaptation (Biesbroek et al., 2011) and future coordination of implementation in the same framework with other policy domains (Biesbroek et al., 2010). As a multidimensional issue involving many state and non-state actors functioning on varying scales of global, national and local levels, a coordination of roles and responsibilities enhances institutional networking for effective implementation of climate change adaptation (Koch et al., 2007; Amundsen et al., 2010). The creation of larger governance networks through coordination is reported to expand the adaptive capacity of local actors (Keskitalo and Kulyasova, 2009), as well as enhancing learning opportunities for policy formulations (Owen, 2010).

As systems evolve to handle problems that surpass contemporary political/administrative systems and boundaries, governance serves as an adaptive tool in generating thrust and empowering communities in a collective vision to effectively and coherently respond to emerging issues of climate change in mitigation and adaptation (Meadowcroft, 2009), using justifiable manners in the attribution of benefits and responsibilities under differentiated capabilities (Paavola and Adger, 2006). The quality of governance of adaptation is increasingly relevant under different strategies of responding to climate change and reducing greenhouse gas emissions in ways that foster complementarity rather than counteraction, building synergies, and reducing trade-offs (Laukkonen et al., 2009). With a centralized national planning that has dominated climate change adaptation strategies such as NAPAs, NAPs etc., governance plays a central role in setting priorities among competing interests, managing inclusion or exclusion, and mediating power relations between various actors that often influences fairness or skewedness in the distribution of benefits. Capturing various perspectives of multiple stakeholders and actors holding different views, power and influence, is pivotal in mutually achieving short-term coping needs and long-term adaptation to climate change (O'Brien et al., 2008).

Governance of adaptation thus creates the space and conditions for achieving specific goals or collective outputs by aligning principles and norms for regulations, decision making procedures and organizations in providing an overarching system to comprehensively address a challenge (Biermann et al., 2009). As a dynamic process, changes in resource regimes under human-environment interactions exposed to climate impacts must be matched with timely institutional reforms in exploiting the windows of opportunities for planned interventions (Young, 2010; DeWulf et al., 2011). Against uncertainties of system response to climate impacts, coordination in resource extraction such as fishery, forestry, watersheds, etc., in deciding on flexibility in management regimes, capacity adjustment schemes and the regulations implemented are important adaptation measures (Mcllgorm et al., 2010). This thus draws on either a centralized guidance of collective action or using subunits in a decentralized system which are both effective based on the circumstances of application (OECD, 2004; Underdal, 2010).

The perturbations triggered by the changing climate to both human and natural systems equally affect current institutions prompting institutional changes in adapting to the changes (Dovers and Hezri, 2010). Except for

prioritizing interventions in national plans and strategies in favor of most vulnerable communities or sectors, there is no evidence of a risk-sharing framework underlying any adaptation planning process. This remains a contentious issue as inter-generational and intra-generational equity and ethical responsibility take hold on the governance process of climate change (Beckman 2008; Page 2008), which undermines the legitimacy and effectiveness of some of the decisions and measures put in place (Paavola, 2008a).

15.4.3. Sustaining Adaptation Implementation

Public-private partnerships are considered to favor sustainable outcomes of the implemented actions for adaptation but are not without their challenges. There are also opportunities such as injecting competitive networks capable of spurring innovative and dynamic governance of sustainability (Smith and Fischlein, 2010). The sustainability of private-public partnership is built on the effectiveness of the governance scheme driving the partnership as is the case of a tropical forest, whereby actions at local levels could have direct implications at the global level, and vice versa, e.g., in REDD+, following the nuances of the uniqueness of time and place (Van Laerhoven, 2010). Characterized by multiple users and uses of tropical forest goods and services under different access rights and ownership patterns, governance could minimize trade-offs under asymmetric power configurations and sustaining implemented adaptation actions (Agrawal et al., 2008). In avoiding a disproportionate risk burden in shared natural resource systems by poorly dependent communities such as in water basins, the devolution of management rights to local communities is considered as a measure for sustainably internalizing risks, enhancing the resilience and adaptive capacity of local communities (Engle and Lemos, 2010), and providing equity and justice (Thomas and Twyman, 2005) especially when captured in planning adaptation.

15.4.4. Feedback and Adjustment Mechanism

Effective governance thus provides safeguards to social-ecological thresholds surrounded by uncertainties, surprises and complex causalities capable of tipping the system. Migration, for example, carries the flip sides of a tested adaptive response (Barnett and Webber, 2010), as well as a risk source of vulnerability to natural resource system thresholds some of which are characterized by slow-onsets (Warner, 2010) which could be addressed with policy and institutional governance (Paavola, 2008b). There is historical evidence of mobility and population distribution as adaptive responses to environmental challenges especially among African herdsmen (Tacoli, 2009; Nakashima et al., 2012). However, the effectiveness of such a technique for adaptation is viewed as generating new risks and security concerns (Brown et al., 2007). Characterized by uncertainties and surprise events, the approaches for adaptation in adjustment to future climate change are considered in the literature to have inescapable feedback trade-offs, such as efficiency over equity or equity over cost and legitimacy, etc. (Adger et al., 2009a).

Joint planning, co-management or co-implementation are considered as cost-effective measures in addressing common risks, especially common pooled resource risks, using collective action such as transboundary water river basins (Wiering et al., 2010). This has resulted in regional initiatives such as in Europe through the EU for example, and other bilateral cross-border co-operation drawing on interdependencies and transnational actors sometimes operating in a political sphere, and steering a process outside of national jurisdictions but contributing to national interests (Andonova et al., 2009).

15.5. Research Needs for Maximizing Opportunities

This chapter reviewed the literature on climate change adaptation (CCA) to assess the progress and limitations of adaptation planning and implementation being undertaken at present. The focus of this chapter is on assessing cases at different levels, from international to local in various sectors from different aspects such as present status and characteristics of CCA planning and implementation, barriers and opportunities to adaptation, capacity for adaptation and capacity-building, and governance of adaptation. Research has identified major issues in moving from planning to implementation which concern reconciling short-term and long-term goals for vulnerability

reduction, overcoming the disconnect between local risk management practices and national institutional and legal frameworks, including mandates policy and planning.

The literature is clear that adaptation planning is transitioning from a phase of awareness and promotion to the construction of concrete responses in societies. The combined efforts of a broad range of international organizations, scientific reports, and media coverage and the very important, occurrence of ongoing extremes event impacts such as Hurricane Sandy and the Drought of 2012 in the US, have raised the importance of adaptation to climate change. In agreement with Biesbroek et al. (2010) and this Chapter, several strategies cite the possible economic damage of unavoidable climate change as a major motivating factor for action, however, few, if any, strategies actually analyze the costs of adaptation. New non-traditional areas of international concern are emerging in the area of national security and economy and trade and receiving increasing attention but are not yet amenable to assessment.

In the literature, more national-level plans and adaptation strategies for developed countries are mentioned than for developing countries; whereas, more implementation cases are documented at the local level in developing countries. Most national strategies appear to be based on potential impacts derived from international and national assessments without consistent and systematic use of regional climate scenarios (Biesbroek et al., 2010; Pulwarty et al. 2012; Chapter Regional Context). At the same time, as the social dimensions of adaptation have attracted more attention, it is emphasized to make the linkages between adaptation and development more explicit to link adaptation planning with co-benefits for development. Different sectors (e.g., disaster risk reduction, water resource planning, agriculture, urban planning) treat adaptation within their traditional context of planning to various degrees and a few are attempting to reconcile various model projects for risk analysis (e.g. Barsugli et al., 2012).

Separating investments that have been applied solely “adaptation” as opposed to “development” has proven difficult in many cases, particularly in defining or attributing the specific component that contributes to climate change adaptation funding beyond benefits to development per se. Studies comparing both formal adaptation plans and less formal adaptation studies several cities demonstrates that the focus is mostly on risk reduction and the protection of citizens and infrastructure, with very few such as Rotterdam seeing adaptation as opportunity for transformation (Heinrichs et al., 2011). Other sectors such as energy, transport, and built infrastructure remain less engaged.

Major investments in infrastructure projects designed to adapt to weather related hazards are being undertaken without awareness of the impacts of climate change on long-term sustainable development (Lasco et al., 2009). The reasons for the initial of attention have been identified as limited public awareness regarding practical links between poverty reduction and adaptation to climate change, and a perception of climate change adaptation as being, “expert driven” and limited to technological responses to identified changes in climate variables (Crabbé and Robin, 2006; Klein et al., 2007) although this is gradually changing (UNISDR, 2011; IPCC, 2012). Barriers to implementing climate change adaptation strategies in Mozambique resulted from differing perceptions of climate risk between farmers and policy-makers, and the perceived potential for negative consequences of the proposed adaptation plans.

Many climate-sensitive sectors in developing countries and marginalized communities in developed countries are currently not well adapted to the risks from current climate. For example, an area may have no or inadequate protection from current climate risks such as floods and drought. This has been termed the adaptation deficit (Burton and May, 2004). Most planning assessments do not include additional costs of reducing present vulnerability to a desired level. Most significantly lack of resources and analytical capabilities to deal with present risks has led to outsourcing of local adaptation plan development. These can generate acontextual recommendations, lacking both the social and historical contexts of a communities experience with climatic risks and more reliance on technological fixes (Crabbé and Robin, 2006; UNISDR, 2011; Pulwarty and Verdin, 2013). For example, despite the intention that city adaptation responses aim at an integrated approach, they tend to have sectoral responses, with limited integration of local voices.

Although national adaptation responses have diverse processes and outcomes in both developed and developing countries, the national level plays a key role in adaptation planning and implementation. NAPAs of developing countries are favorably viewed as being country-driven in their development. Many NAPAs propose adaptation strategies that are almost identical with standard development projects. Bottom-up approaches are particularly useful in efforts seeking to reduce social vulnerability and addressing adaptation to climate change as a process. However,

adaptation to climate change also requires complementary top-down strategies through different levels of governments. Another feature is that good practices have emerged in developing countries. Adaptation efforts in some countries, such as Bangladesh, Cambodia, Bhutan, and the Maldives, which are linked to development funding, provide a 'win-win' adaptation strategy that strengthens resilience to climate change while improving economic stability and environmental quality. However, securing the long-term financing for ongoing adaptation is rarely addressed beyond the project phase.

Urban areas are showing progress of CCA planning and implementation. A growing number of adaptation plans are reported, and urban areas are the focus of a number of local planning initiatives. Urban areas tend to formalize and institutionalize their work through the establishment of dedicated climate units, either within a relevant department or as a separate and cross-cutting office. However, with some exceptions, few local governments have had the resources, capability, and coordination to institutionalize adaptation to climate change.

Monitoring and early warning systems designed to inform social learning play important roles in helping to adjust adaptation implementation, especially on the local scale. Viewing risk communication as a social process allows for effective participatory approaches, network- building and the production of visual, compelling and engaging information for use by local stakeholders. The lack of coordination in the scale of governance together with unclear division of tasks and responsibilities of actors, especially under conflicting timescales of interventions e.g. emergency versus adaptive, are significant barriers to adaptation and future coordination of implementation.

A no-regrets approach based on co-benefits to emphasize on disaster risk management are increasingly advocated. However, climate change adaptation and disaster risk reduction are, at present, handled by separate agencies, although they share similar objectives and challenges. The experience on adaptation to date illustrates the need for better coordination and the development of collaborative networks. Developing frameworks and metrics for evaluating adaptation, that is cognizant of the experience in disaster risk, integrated watershed, coastal zone and the natural and social capita experience and literatures remain a central need. The potential for ecosystem-based approaches is also increasingly being realized (e.g. Munroe et al., 2011) offering opportunities that integrate with or even substitute for the use of engineered infrastructure or other technological approaches. Examples include sustainable water and habitat management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced base-flows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Midgley et al., 2012; Opperman et al., 2009). The most significant contributions of ecosystem-based approaches may lie in allowing for flexibility as rapid transitions and thresholds are met, and in lowering the risk of maladaptation by substituting for or delaying the need for engineering solutions. Although the importance of evaluation of this area in adaptation is recognized, it is under-researched.

Most critical is the need for research to inform practice on the governance, including the leadership of and public engagement in adaptation. As a multidimensional concern involving many state and non-state actors and decisions, functioning on varying scales of global, national and local levels, improved multilevel governance offers the chance to identify options for moving from reactive to proactive adaptation processes.

Frequently Asked Questions

FAQ 15.1: What is the present status of climate change adaptation planning and implementation across the globe?

Climate change adaptation has been brought to people's attention due to the recent media coverage and various reports, leading to a growing number of adaptation plans both in developed and developing countries. The assessment of literature indicates adaptation planning is transitioning from a phase of awareness and promotion to the construction of concrete responses in societies. There is a wide range of adaptation plans reflecting the specific context, needs, values, and perceptions of societies. More national-level plans and adaptation strategies have been established in developed countries than in developing countries; whereas, more implementation cases are reported at the local level in developing countries. The plans developed by developing countries appear to focus more on climate change impacts and disaster risk management, where urban areas have become the focal point in local

planning initiatives. However, except for large cities, few local governments have the resources, capability, and coordination ability to institutionalize adaptation to climate change. In spite of these limitations, early discussions of the transformations needed in the structure and operational culture of institutions to address adaptation to climate change are occurring in both developed and developing countries. Monitoring, evaluating, and reviewing adaptation planning and implementation are critical aspects of complex adaptation planning as a social process.

FAQ 15.2: How are climate change policies operationalized at different scales (e.g., international, national, and local)?

National and subnational plans are developed by many developed countries and more and more plans are being produced by developing countries through the National Adaptation Programmes of Action (NAPA) and the National Adaptation Plans (NAPs). What lacks is the mechanism and institutional capacity to bridge between the national/sub-national level and the local level adaptation planning. NAPAs of developing countries are favorably viewed as being country-driven in their development. Many NAPAs propose adaptation strategies that are almost identical with standard development projects. Bottom-up approaches are particularly useful for reducing social vulnerability and addressing adaptation to climate change as a process. However, adaptation to climate change also requires complementary top-down strategies through different levels of governments to realize mainstreaming adaptation. Sustainable development and disaster risk management are two approaches to incorporate adaptation planning into these various levels, and these themes are particularly important and relevant at the local community in developing countries. In general, progress has been slow with regard to integrating disaster risk management and climate change adaptation at the national, subnational, and local level. To overcome such gaps, better coordination between risk management agencies and climate change adaptation efforts is needed.

FAQ 15.3: What capacities currently exist for implementing climate change adaptation?

In general there are two sources of adaptive capacity: institutional and organizational support, and science and technology. Adaptation capacity is supported by adaptation governance which occurs at multiple scales: international, national, sub-national, and local. Integrating and coordinating adaptation planning and implementation across these vertical levels of governance provides one big challenge while doing the same across different sectors (e.g., disaster risk reduction, water resource planning, agriculture, urban planning) and different sections or departments of a government provides yet another challenge. For successful implementation of adaptation plans, it is needed to promote both vertical and horizontal integration and coordination of adaptation planning across different governance levels and sectors. Science and technology provide another source of capacity. Development and diffusion of new technologies and management practices expands the range of adaptation possibilities by increasing opportunities or reducing costs. Knowledge development and sharing includes the development of science and new technologies, early warning systems, technology transfer and diffusion, education and training, and the use of local and traditional knowledge.

Cross-Chapter Box

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based approaches to adaptation (also termed Ecosystem-based Adaptation, EBA) integrate the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe *et al.*, 2011; Munroe *et al.*, 2011). EBA is implemented through the sustainable management of natural resources, as well as conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls *et al.*, 2009). The CBD COP 10 Decision X/33 on Climate Change and Biodiversity states further that effective EBA also "takes into account the multiple social, economic and cultural co-benefits for local communities".

The potential for EBA is increasingly being realized (e.g., Munroe *et al.*, 2011), offering opportunities that integrate with or even substitute for the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees, may adversely affect biodiversity, resulting in maladaptation due to damage to ecosystem regulating services (Campbell *et al.*, 2009, Munroe *et al.*, 2011). There is some evidence that

the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). Well-integrated EBA is also more cost effective and sustainable than non-integrated physical engineering approaches, and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. EBA also offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes.

EBA provides opportunities particularly in developing countries where economies depend more directly on the provision of ecosystem services (Vignola *et al.*, 2009), to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang *et al.*,). In these settings, ecosystem-based adaptation projects may be readily developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan *et al.*, 2012, Midgley *et al.*, 2012; Roberts *et al.*, 2012)

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Midgley *et al.*, 2012, Opperman *et al.*, 2009).
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands and deltas) to provide effective measure against storm-surges, saline intrusion and coastal erosion;
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding;
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques;
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

It is important to assess the appropriate and effective application of EBA as a developing concept through learning from work underway, and to build understanding of the social and physical conditions that may limit its effectiveness. Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang *et al*. (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.]

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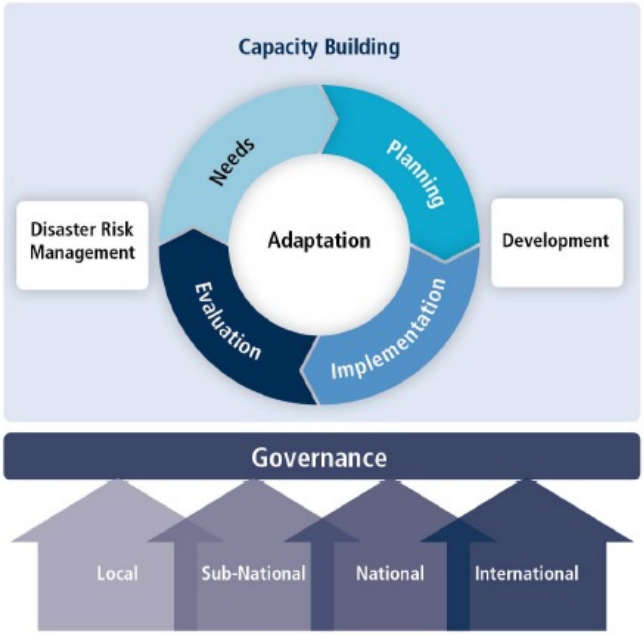

Figure 15-1: Four main phases of adaptation planning and implementation: needs, planning, implementation, and evaluation. This is a cyclic, iterative process. Building capacity to respond to change, whether expected or unexpected, creates resilience in societies to cope in the face of uncertainties in climate change projections. Efforts in adaptation need to be linked with development or disaster risk management. This is particularly true and important in developing countries. Adaptation governance underlies the capacity and governance takes place at multiple scales: international, national, sub-national, and local.

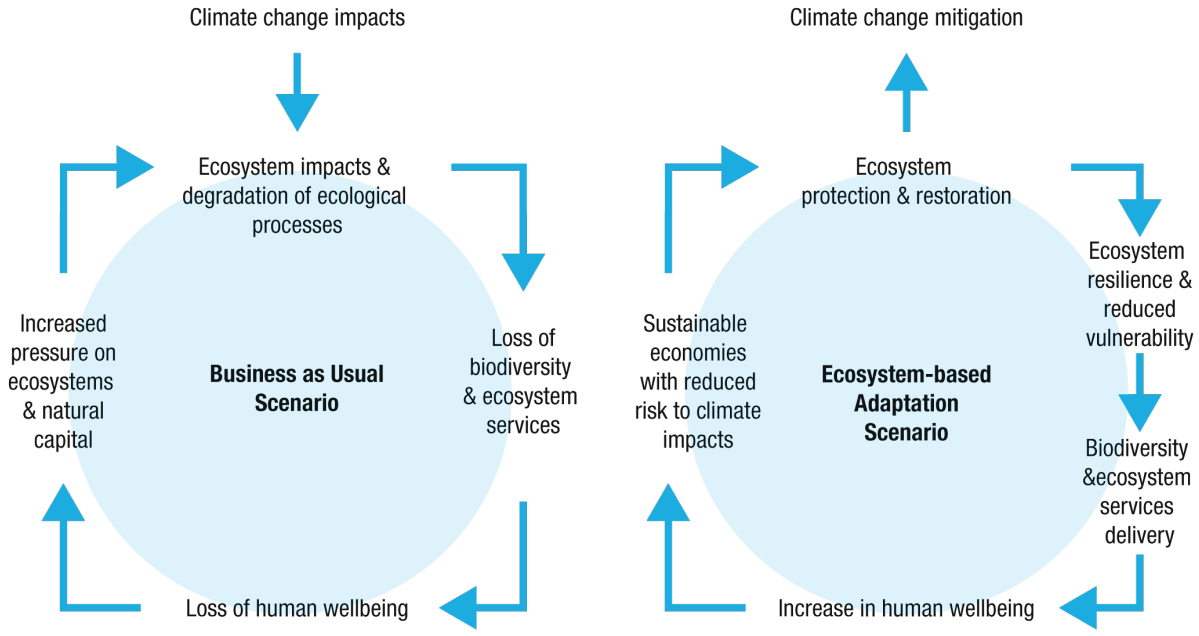

Figure EA-1: Adapted from Munang *et al*. (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.

Chapter 16. Adaptation Opportunities, Constraints, and Limits

Coordinating Lead Authors
Richard J.T. Klein (Sweden), Guy F. Midgley (South Africa), Benjamin L. Preston (USA)

Lead Authors
Mozaharul Alam (Bangladesh), Frans G.H. Berkhout (Netherlands), Kirstin Dow (USA), Yu'e Li (China), M. Rebecca Shaw (USA)

Contributing Authors
Wouter Botzen (Netherlands), Halvard Buhaug (Norway), Karl W. Butzer (USA), Carina Keskitalo (Sweden), Sarshen Marais (South Africa), Robert Muir-Wood (UK), Johanna Mustelin (Finland), Hannah Reid (UK), Lauren Rickards (Australia), Tim F. Smith (Australia), Paul Watkiss (UK), Johanna Wolf (Germany)

Review Editors
Habiba Gitay (Australia), James Thurlow (South Africa)

Volunteer Chapter Scientists
Seraina Buob (Switzerland), Adelle Thomas (Bahamas)

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Frequently Asked Questions
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16.2: To what extent can sustainable economic development, innovation, and technological change reduce adaptation constraints and contribute to the avoidance of limits?
16.3: Are limits to adaptation predictable?
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Cross-Chapter Box
CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

References

Executive Summary

A range of factors constrain the planning and implementation of adaptation actions and potentially reduce their effectiveness (*high agreement, robust evidence)*. The availability of resources for adaptation continues to feature strongly in the adaptation literature as a significant constraint on adaptation, as does uncertainty regarding future climate and disaster risk at national and regional scales. However, there is increasing awareness within the literature of the dynamics of social processes and governance that mediate the entitlements of actors to resources and promote social learning regarding adaptation. The manner in which these constraints manifest and their implications for the capacity of an actor to achieve adaptation objectives vary significantly across different regions and sectors as well as across different social and temporal scales. Some constraints to adaptation are a consequence of inherent trade-offs among different perceptions of risk and the allocation of finite resources, and therefore, adaptation efficiency and effectiveness may often be less than optimal. [16.2, 16.3]

Evidence from both natural and human-managed systems demonstrates the existence of limits to adaptation to climatic and other related environmental and socio-economic risks (*high agreement, robust evidence*). Archeological and historical evidence is providing growing insights into periods of societal change, including catastrophic societal failures, in which climate change or variability may have been a contributory factor. Such evidence indicates that socioeconomic and cultural factors mediate societal responses to emergent risks such as changes in climate and influence the likelihood of limits to adaptation being reached and exceeded. [16.3, 16.5, 16.5.1, 16.5.2, 16.8, Box16-3]

Limits to adaptation emerge as a result of the interaction between climate change and other biophysical and socioeconomic constraints (*high agreement, robust evidence*). Recent studies have provided valuable insights regarding the presence of so-called 'tipping points', 'key vulnerabilities', or 'planetary boundaries' for the Earth system. While these biophysical thresholds represent an important determinant of limits to adaptation, particularly for natural systems, socioeconomic conditions and trends also contribute to the definition of limits in social systems. In particular, demographic change as well as economic development will influence future human vulnerability and adaptive capacity, but the externalities of these processes may reduce the resilience of natural systems to adapt to a changing climate. [16.2, 16.3, 16.4]

Much of the literature identifying limits to adaptation for specific systems and/or management objectives are associated with biophysical systems, particularly ecosystems and/or individual species that are dependent upon specific biophysical regimes (*high agreement, robust evidence*). Those species that already persist at the

edge of their thermal and/or hydrological limits are likely to be most vulnerable to a changing climate. Species do have the capacity to adapt through phenotypic and genetic responses. The physiological and/or ecological thresholds imposed by climate effectively represent 'hard' limits in that no adaptation options can be implemented to enable sustainability once thresholds are exceeded. As a broad range of human values and managed systems are dependent upon ecosystems goods and services, 'hard' limits in ecological systems have the potential to constrain or limit adaptation in socioeconomic systems. [16.4.1]

Social limits to adaptation are dynamic over space and time due to normative judgments and values of actors, technological change, and emergent properties of complex systems (*high agreement, low evidence*). Limits to adaptation are likely to be exceeded locally before being exceeded regionally and at larger spatial scales. This should provide regional, national and international actors with an early warning of possible future adaptation constraints and limits. Some adaptation limits may be removed over time due either to changing normative judgments and values of actors which lead to the abandonment of previously held objectives, or through technological advancement. However, some actors may find that transformational changes are required that necessitate trade-offs in some values in order to preserve others [16.4.1, 16.4.2]

The greater the magnitude of climate change, the greater the likelihood that adaptation will encounter limits (*high agreement, low evidence*). Mitigation and adaptation are complementary strategies. Greater adaptation efforts will be required to achieve the objectives of actors if mitigation efforts are not successful in avoiding high magnitudes of climate change. There are, however, limits to the extent to which adaptation could reduce the impacts not avoided by mitigation, and residual loss and damage is may occur despite adaptive action. Knowledge about limits to adaptation could therefore inform the level and timing of mitigation and might justify early mitigation action. However, as the future capacity of actors in different sectoral and regional contexts to adapt to climate change remains uncertain, the implications of adaptation for mitigation demand will be contingent upon economic development pathways and investments made to enhance the adaptive capacity of vulnerable actors. [16.3.1.2, 16.5, 19.6, 19.7, 20.5.3]

The capacity to describe and predict limits to adaptation is significantly impaired by the complexity of socio-ecological systems (*high agreement, low evidence*). While there is high agreement that limits to adaptation exist, detailed understanding of the level at which climate change impacts may impose an intolerable risk to social objectives (the definition of adaptation limits adopted here) is available only for a small number of ecosystems and crop species. Any assessment of limits to adaptation in human systems is preliminary because of uncertainty about the existence and level of adaptation limits, and whether these limits are hard or soft. Furthermore, social, economic and cultural trends and conditions, including uncertainty regarding actors' objectives and values and how they evolve over time further confound explicit definitions of limits. Thus while climate change raises 'reasons for concern' regarding the sustainability of various natural and human systems, there is little evidence to support climate thresholds, such as a 2°C increase in global mean temperature, as being robust definitions of limits to adaptation. [16.4.2]

Opportunities exist for actors at all geographical and institutional levels and in different development contexts to facilitate, initiate and implement effective adaptation action (*medium agreement, medium evidence*). Adaptation action at all levels – from households, firms or municipalities to national government agencies and regional economic integration organizations – is influenced by resources made available by third parties, including the sharing of knowledge and information, the transfer or technologies, and the provision of financial resources. In addition, national and international public policy can encourage the preparation and implementation of national adaptation strategies. Mainstreaming adaptation into planning and decision-making, including official development assistance, is an opportunity for enhancing the effectiveness and efficiency of adaptation investments. [16.6]

Avoiding limits to adaptation is a complex management challenge necessitating new integrative forms of risk governance (*medium agreement, low evidence*). Limits to adaptation are influenced by cultural, institutional and socio-economic factors. Consequently avoiding limits will necessitate policy responses and awareness that goes beyond greenhouse gas mitigation and adaptation responses alone. Driving forces such as inequality and the disproportionate vulnerability of marginalized actors to climate-related disasters and catastrophic losses will need to

be addressed. Hence, a portfolio of local, national, and international strategies will be needed to facilitate sustainable development that expands the range of climate to which socio-ecological systems can adapt. [16.4, 16.6, 16.7]

16.1. Introduction and Context

Since the IPCC's *Fourth Assessment Report* (AR4), demand for knowledge regarding the planning and implementation of adaptation as a strategy for climate risk management has increased significantly ((Park *et al.*, 2011; Preston *et al.*, 2011a). This chapter assesses the latest literature on biophysical and socioeconomic constraints on adaptation and the potential for such constraints to pose limits to adaptation. It also examines the circumstances that create opportunities for adaptation and the ancillary benefits that may arise from the implementation of adaptation policies and measures. Given increasing evidence of potential limits to adaptation, the chapter also examines the literature on transformation as a consequence of, or response to, adaptation limits.

To facilitate this literature assessment, this chapter provides an explicit framework for conceptualizing opportunities, constraints, and limits (16.2). In this framework, the core concepts including definitions of adaptation, vulnerability, and adaptive capacity are consistent with those used previously in the AR4. However, the material in this chapter should be considered in conjunction with that of other complementary AR5 WGII chapters. These include Chapter 14 (*Adaptation Needs and Options*), Chapter 15 (*Adaptation Planning and Implementation*), and Chapter 17 (*Economics of Adaptation*). Material from a range of other WGII chapters is also relevant to informing adaptation opportunities, constraints, and limits, particularly Chapter 2 (*Foundations for Decision-Making*) and Chapter 19 (*Emergent Risks and Key Vulnerabilities*). Furthermore, while this chapter synthesizes material from each of the sectoral and regional chapters, readers are encouraged to refer directly to those chapters for more detailed information.

In order to enhance the policy relevance of the assessment of adaptation opportunities, constraints, and limits, this chapter takes as its entry point the perspective of actors as they consider adaptation response strategies over near, medium and longer terms (Dow *et al.*, 2013; Dow *et al.*, In Press). Actors may be individuals, communities, organizations, corporations, NGOs, governmental agencies, or other entities responding to real or perceived climate-related stresses or opportunities as they pursue their objectives (Patt and Schröter, 2008a; Blennow and Persson, 2009; Frank *et al.*, 2011). These actors may seek to implement near-term adaptation policies and measures under constraining circumstances while simultaneously anticipating or working to alleviate those constraints to enable greater flexibility and adaptive capacity in the future. Therefore, it is necessary to consider diverse timeframes for possible social, institutional, technological and environmental changes. These timeframes also differ in the types of uncertainties that are relevant, ranging from those of climate scenarios and models, possible thresholds, nonlinear responses or irreversible changes in social or environmental systems, and the anticipated magnitude of impacts associated with higher or lower levels of climate change (Meze-Hausken, 2008; Hallegatte, 2009a; Briske *et al.*, 2010).

The range of adaptation options available to actors to achieve their objectives vary with capacities, social context and the dynamics of climate-environment interactions. Hence, a robust understanding of adaptive capacity is necessary to evaluate adaptation needs and options (Chapter 14) and the challenges associated with their implementation (Chapter 15). The manner in which actors frame adaptation and their objectives also influences adaptation processes. Much of the dialogue on adaptation has focused on incremental adaptation, wherein actors aim to make adjustments to management practice and behavior to secure status quo values and objectives (Garrelts and Lange, 2011). Such adaptation may include portfolios of responses as it may not be possible to completely 'climate proof' a system, making insurance or other support mechanisms important means of building resilience. However, some adaptations may encounter future constraints or limits by promoting lock-in to a technology or fostering path dependence around a set of strategies, which can lead to maladaptation (Berkhout, 2002; Barnett and O'Neill, 2010; Eriksen *et al.*, 2011). Hence, the adaptation discourse has recently expanded to consider more transformational framings of adaptation associated with fundamental changes in actors' objectives or values to shift from a position of increasing vulnerability to one of increasing opportunity (Stafford Smith *et al.*, 2011; Pelling, 2011; Park *et al.*, 2011; Kates *et al.*, 2012; O'Neill and Handmer, 2012).

To provide further background and context, this chapter proceeds by revisiting relevant findings on adaptation opportunities, constraints, and limits within the AR4 and the more recent IPCC *Special Report on Managing the Risks of Extreme Events and. Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012). The chapter then presents a framework for adaptation, opportunities, and limits with an emphasis on explicit definitions of these concepts to facilitate assessment. Key components of this framework are assessed in subsequent chapter sections including the synthesis of how these components are treated among the different sectoral and regional chapters of the AR5 WGII report. The chapter concludes with an assessment of the ethical implications of adaptation constraints and limits and a synthesis of what the adaptation literature suggests are pathways forward for research and practice to capitalize on opportunities, reduce constraints, and avoid limits.

16.1.1. Summary of Relevant AR4 Findings

The AR4 *Summary for Policymakers* of Working Group II concluded that there are "*formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation*" and that for developing countries, "*availability of resources and building adaptive capacity are particularly important*" (IPCC, 2007a). These findings were based primarily on Chapter 17, *Assessment of Adaptation Practices, Options, Constraints and Capacity* (Adger *et al*., 2007). The key conclusion from Adger *et al*. (2007), as relevant to this chapter, was as follows: "*There are substantial limits and barriers to adaptation (very high confidence)*". The authors go on to identify a range of barriers including the rate and magnitude of climate change, as well as constraints arising from technological, financial, cognitive and behavioral, and social and cultural factors. The authors also noted both significant knowledge gaps and impediments to the sharing of relevant information to alleviate those gaps.

These findings were further evidenced by the sectoral, and particularly, regional chapters of the AR4 WGII report which provided information regarding the similarities and differences among regions with respect to the manner in which adaptation opportunities, constraints, and limits manifest. For example, the chapters assessing impacts and adaptation in Africa, Asia, and Latin America collectively emphasize the significant constraints on adaptation in developing nations. For Africa, Boko *et al*. (2007) suggest there is evidence of an erosion of coping and adaptive strategies as a result of varying land-use changes and socio-political and cultural stresses. For Asia, Cruz *et al*. (2007) note that the poor usually have very low adaptive capacity due to their limited access to information, technology and other capital assets, making them highly vulnerable to climate change. For Latin America, Magrin *et al*. (2007) find that socio-economic and political factors seriously reduce the capability to implement adaptation options. Meanwhile, the chapter on Small Islands by Mimura *et al*. (2007) identifies several constraints to adaptation including limited natural resources and relative isolation. For all of these regions, adaptation challenges are linked to governance systems and the quality of national institutions as well as limited scientific capacity and ongoing development challenges (e.g., poverty, literacy, and civil and political rights).

The AR4 also provided evidence that constraints on adaptation are not limited to the developing world. For example, Hennessy *et al*. (2007) find that while adaptive capacity in Australia and New Zealand has been strengthened, a number of barriers remain including tools and methods for impact assessment as well as appraisal and evaluation of adaptation options. They also note weak linkages among the various strata of government regarding adaptation policy and skepticism among some populations toward climate change science. Similarly for North America, Field *et al*. (2007) identify a range of social and cultural barriers, informational and technological barriers, and financial and market barriers. The chapter on Europe mentions the limits faced by species and ecosystems due to lack of migration space, low soil fertility and human alternations of the landscape (Alcamo *et al*., 2007). Finally, in the chapter on the Polar Regions, Anisimov *et al*. (2007) note that indigenous groups have developed resilience through sharing resources in kinship networks that link hunters with office workers, and even in the cash sector of the economy. However, they conclude that in the future, such responses may be constrained by social, cultural, economic, and political factors.

A few other AR4 chapters assessed literature relevant to this chapter. Chapter 18 - *Inter-Relationships between Adaptation and Mitigation* (Klein *et al*., 2007) discusses the possible effect of mitigation on adaptation (an issue also considered by Working Group III, in particular by (Fisher *et al*., 2007) and (Sathaye *et al*., 2007)). Finally, Chapter

19 -*Assessing Key Vulnerabilities and the Risk from Climate Change* (Schneider *et al*., 2007) outlines how the presence of adaptation constraints and limits is a contributing factor to vulnerability, possibly resulting in significant adverse impacts. Chapters that address similar themes ablso appear in the AR5, and cross-references are provided in this chapter to this more recent material as appropriate.

16.1.2. Summary of Relevant SREX Findings

The IPCC's SREX report assesses a broad array of literature on climate change, extreme events, adaptation, and disaster risk reduction. A central framing concept for the SREX was the assertion that (Lavell *et al*., 2012 pg. 37),

> *" . .while there is a longstanding awareness of the role of development policy and practice in shaping disaster risk, advances in the reduction of the underlying causes – the social, political, economic, and environmental drivers of disaster risk – remain insufficient to reduce hazard, exposure, and vulnerability in many regions (UNISDR, 2009, 2011) (high confidence)."*

As reductions in vulnerability can arise from either capitalizing on opportunities, relaxing constraints or removing limits to adaptation, this assessment of the relevant SREX material focuses on how the key findings of the SREX provide insights relevant to the treatment of opportunities, constraints and limits in this chapter.

With respect to opportunities, the linkages between development and disaster risk reduction provide a number of avenues for facilitating adaptive responses toward enhanced societal resilience to natural disasters and climate change. For example, the SREX highlights the benefits of considering disaster risk in national development planning and if strategies to adapt to climate change are adopted (Lal *et al*., 2012). The observed dependence of disasters at national and regional scales upon underlying patterns of development are indicative of the opportunities for increasing societal resilience through sustainable development. In particular, incorporating adaptation into multi-hazard risk management may be an effective strategy for the efficient integrated management of natural hazards and future climate risk (O'Brien *et al*., 2012). Disasters provide potential opportunities for reducing future weather- and climate-related risk through disaster response and recovery processes (Cutter *et al*., 2012). Capitalizing on this opportunity often necessitates careful planning for the staging of response efforts to ensure the demand for near-term recover does not jeopardize opportunities for enhanced resilience over the long-term. There may also be opportunities for enhancing international assistance for climate adaptation through more robust finance mechanisms for mainstreaming adaptation into disaster risk management and sustainable development (Burton *et al*., 2012).

The report also provides discussion of the constraints associated with enhancing disaster risk reduction as well as climate adaptation. In particular, ongoing development deficits as well as inequality in coping and adaptive capacities pose fundamental challenges to disaster risk management and adaptation (Cardona *et al*., 2012). Although such challenges can propagate from the bottom up, the SREX notes that national systems and institutions are critical to the capacity of nations to manage the risks associated with climate variability and change (Lal *et al*., 2012). Yet capacity at one scale does not necessarily convey capacity at other scales (Burton *et al*., 2012). Even in the presence of robust institutions, rates of socioeconomic and climate change can interact to constrain adaptation. For example, O'Brien *et al*. (2012) note that rapid socioeconomic development in vulnerable urban areas can increase societal exposure to natural hazards while simultaneously constraining the capacity of actors to implement policies and measures to reduce vulnerability. For many regions, such socioeconomic change may be a greater contributor to vulnerability than changes in the frequency, intensity, or duration of extreme weather events. Overcoming these constraints to achieve development objectives is challenged by a paucity of disaster data at the local level as well as persistent uncertainties regarding the manifestation of extreme events in future decades (Seneviratne *et al*., 2012; Cutter *et al*., 2012).

The SREX also cautioned that natural hazards, climate change and societal vulnerability can pose fundamental limits to sustainable development. Such limits can arise from the exceedance of biophysical and/or societal thresholds or tipping points (Lal *et al*., 2012; O'Brien *et al*., 2012; Seneviratne *et al*., 2012). Accordingly, the SREX concludes that adaptation actions must include not only incremental adjustments to climate variability and climate change but also transformational changes that alter the fundamental attributes of systems of value. Such

transformation may be aided by actors questioning prevailing assumptions, paradigms, and management objectives toward the development of new ways of managing risk and identifying opportunities (O'Brien *et al*., 2012).

16.2. A Risk-Based Framework for Assessing Adaptation Opportunities, Constraints, and Limits

Risk is an intrinsic element of any understanding of "*dangerous anthropogenic interference with the climate system*" (UNFCCC, 1992) and the associated assumptions about the capacity of biophysical systems, social groups and societies to adapt to climatic change. The UNFCCC refers specifically to adaptation of ecosystems, threats to food production and the sustainability of economic development. While there is evidence that there are opportunities to adapt to climate change impacts in natural and human systems, there is also evidence that the potential to adapt is constrained, or more difficult, in some situations, and faces limits in others (e.g. Adger *et al*., 2009b; Dow *et al*., In Press).

Consistent with for the development of risk management approaches to guide adaptation response to climate change (IPCC, 2012) this chapter utilizes a risk-based framework and a set of linked definitions of opportunities, constraints and limits to adaptation (see Box 16-1). A number of different meanings are ascribed to these key terms and these have worked to confuse an important scientific and policy debate. The AR4, for example, used the terms constraints, barriers, and limits interchangeably to describe general impediments to adaptation (Adger *et al*., 2007), and similar ambiguities are evident across the literature (O'Brien, 2009; Biesbroek *et al*., 2009; de Bruin *et al*., 2009a). The integrated set of definitions employed here aims to clarify discussions in this realm. The framework and definitions draw on a number of literatures (Dow *et al*., In Press), in particular vulnerability assessment (Füssel, 2006; Füssel and Klein, 2006a) and risk assessment (Jones, 2001; Klinke and Renn, 2002; Renn, 2008; NRC, 2010) as well as climate adaptation (Hulme *et al*., 2007; Adger *et al*., 2009b; Hall *et al*., 2012).

Building on the risk management approach, we present a set of definitions of opportunities, constraints and limits to adaptation. An explicit focus on risk is particularly useful to understanding climate adaptation. Adaptation is intended to reduce the risk to things we value (Adger *et al*., 2012b). The concept of risk integrates the dimensions of probability and uncertainty with the material and normative dimensions that shape societal response to threats. The framing is grounded in an actor-based perspective which acknowledges that social actors from individuals to agencies or governments, and biophysical entities from species to habitats to ecosystems have different objectives and resources with respect to adaptation.

Figure 16-1 relates judgement about risk and the ability to maintain risks at a tolerable level to the concept of adaptation and adaptation opportunities, constraints, and limits (Box 16-1). Drawing on the work of Klinke and Renn (2002)(2002), we view individual actors as addressing risks in one of three categories. Acceptable risks are risks deemed so low that additional efforts at risk reduction, in this case climate adaptation efforts, are not justified. Tolerable risks relate to situations where adaptive, risk reduction efforts are required and effective for risks to be kept within reasonable levels. The scope of risks that fall within the tolerable area is influenced by adaptation opportunities and constraints. As discussed further in sections 16.3 and 16.7, these opportunities and constraints may be physical, technological, economic, institutional, legal, cultural, or environmental conditions(Yohe and Tol, 2002; Meze-Hausken, 2008; Patt and Schröter, 2008a; Adger *et al*., 2009b; Moser and Ekstrom, 2010; Adger *et al*., 2012a; Adger *et al*., 2012b). Constraints may limit the range of adaptation options leaving the potential for 'residual damages' which nevertheless are deemed to remains at a tolerable level. There are also a host of perceptual, economic and institutional factors that determine whether or not organizations in the private or public sectors choose to adapt to reduce potential vulnerabilities or avoid climate change impacts (Ivey *et al*., 2004; Naess *et al*., 2005; Moser *et al*., 2008; Storbjork, 2010; Farley *et al*., 2011; Berrang-Ford *et al*., 2011; Berkhout, 2012) (Also see AR5 2.2; 14.4; 16.3.1.1; 17.3). In particular, the economic and other costs of adaptation may be perceived to outweigh the uncertain future benefits of adaptation. Within this category, some level of residual damage following adaptation may be tolerable (Stern *et al*., 2006; de Bruin *et al*., 2009a)

[INSERT FIGURE 16-1 HERE
Figure 16-1: Conceptual model of the determinants of acceptable, tolerable and intolerable risks and their implications for limits to adaptation (Dow *et al*., 2013); based on (Klinke and Renn, 2002).]

Intolerable risks to existing objectives and needs are those which, despite adaptive actions, pose threats of such combined frequency and intensity that an actor would avoid them or, if feasible and appropriate, act in the societal interest to prohibit them. Whether it is an individual's decision to relocate, an insurance company's decision to withdraw coverage, or a lack of managed adaption strategies for a species, these actions represent a discontinuity in behaviour symptomatic of reaching an adaptation limit. The alternative to such discontinuities of disposition or behaviour is escalating risk of losses (16.4.2). While actors have their own judgements of what are acceptable, tolerable or intolerable risks, collective responses often shape the constraints and opportunities to adaptation and responses to risk through the distribution of resources, institutional design, and support of capacity development (16.3). If these risks and discontinuities have global-scale consequences, they can be linked to 'key vulnerabilities' to climate change (see Chapter 19). Consistent with our framing of adaptation limits as being actor-centered, such key vulnerabilities would need to be assessed in terms of the adaptation limits which they imply for specific social actors, species and ecosystems.

_____ START BOX 16-1 HERE _____

Box 16-1. Definitions of Limits, Opportunities, and Constraints to Adaptation

Adaptation Limit: *The point at which an actor's objectives (or biophysical system needs) cannot be secured from intolerable risks through adaptive actions* (Dow *et al.*, 2013).
A limit to adaptation means that no adaptation options exist, or an unacceptable measure of adaptive effort is required to secure objectives, or to allow for a species or ecosystem to survive in an unaltered state. Examples of objectives include, for instance, standards of safety codified in laws, regulations, or engineering design standards (*e.g.,* 1 in 500 year levees), security of drinking water supplies as well as equity, cultural cohesion, and preservation of livelihoods. Requirements of biophysical systems might include a maximum temperature or precipitation levels. That ability to avoid adaptation limits is shaped by adaptation opportunities and constraints.

Adaptation Opportunity: *factors that make it easier to plan and implement adaptation actions.*
Opportunities are the opposite of constraints. Adaptation opportunities create new potential for an actor to secure their existing objectives, or for a biophysical system to retain productivity or functioning. New circumstances, such as public or private interventions, may make it possible or easier to pursue successful adaptation. Adaptation opportunities are distinct from co-benefits and from opportunities arising from climate change (e.g., longer growing seasons), which would commonly be referred to as potential benefits of climate change (see chapter 17) or adaptation options (see Chapter 14).

Adaptation Constraints: *factors that make it harder to plan and implement adaptation actions.*
Adaptation constraints restrict options for an actor to secure their existing objectives, or for a biophysical system to maintain productivity or functioning. These constraints commonly include lack funding, technology or knowledge, or institutional traits that restrict some actions (see 16.3) or lack of connectivity for ecosystems. The terms "barriers" and "obstacles" are frequently used as synonyms.

_____ END BOX 16-1 HERE _____

It is essential to evaluate opportunities, constraints, and limits with respect to the rate and magnitude of climate change and within the relevant time horizon for an actor, a species or an ecosystem. Opportunities, constraints and limits to adaptation develop along a dynamic continuum, together conditioning the capacity of natural and human systems to adapt to climate change. New opportunities may emerge through time, constraints may be loosened, and some, although not all, limits may be shifted or removed altogether. Climate variability and change and associated patterns of impacts are also changing at diverse and non-linear rates. For a given social actor, the timeframe for adaptation decisions usefully bounds an analysis of opportunities, constraints and limits. Each year, for example, US Great Plains farmers chooses if, when, and what to plant and how much insurance to purchase. While more drought-resistant crop varieties might become available in future, the choice in any given year is limited to the varieties currently available. A community that has suffered severe storm damage must act urgently to restore homes and infrastructure using the technologies, financial resources and institutions then available. Changing institutional

relationships may make greater amounts of disaster recovery aid available to support other adaptation choices in future, but if there are immediate safety needs, delay in expectation of these changes would be hard to justify. For natural ecosystems, the rate of species responses relative to change in environmental conditions bounds the capacity to adapt. The observed rate of evolutionary and other species responses ranges from rapid to inadequate to allow persistence (Hoffmann and Sgro, 2011), but the knowledge base is insufficient to permit clear general conclusions for ecosystem adaptation capacity.

Because adaptation limits relate to adaptation resources and attitudes to risk and threat which may change over time, some limits may be viewed as "soft". While a given adaptation option may not be available today or require impracticable levels of effort, it may become available through innovation or changes in attitudes in time. Soft limits may be shifted investments in research and development, changes in regulatory rules or funding arrangements, or by changing social or political attitudes. Other limits are "hard" in that there is no known process to change them. Examples of fixed limits include water supply in fossil aquifers, the range of a species, limits to retreat on islands, loss of genetic diversity, or the tolerance of coral species to temperature and ocean acidity.

16.3. Adaptation Capacities and Constraints

There is *high agreement and robust evidence* that different actors, sectors, and geographic regions have differential capacities to adapt to climate variability and change (Adger *et al*., 2007; IPCC, 2012), although those capacities can be difficult to measure (Tol *et al*., 2008; Hinkel, 2011). Since the AR4, the literature on adaptive capacity and adaptation constraints has deepened (Adger *et al*., 2009b; Moser and Ekstrom, 2010). This literature can be divided into two general categories of constraints (Figure 16-2). One focuses on interactions among biophysical and socioeconomic processes that may span multiple actors across different spatial or temporal scales. These processes evolve constantly over time and establish the context in societal context for adaptation. The second category focuses on the entitlements of actors to the assets and capital necessary for the implementation of specific adaptation policies and measures (Yohe and Tol, 2002; Paavola, 2008; Osbahr *et al*., 2010). These two categories of constraints as well as specific examples are discussed further in the following sections.

[INSERT FIGURE 16-2 HERE
Figure 16-2: Identification of key adaptation constraints considered in this chapter, which are categorized into two groups. One reflects constantly evolving biophysical and socio-economic processes that influence the societal context for adaptation. These processes subsequently influence the implementation of specific adaptation policies and measures that could be deployed to achieve a particular objective.]

Specific constraints associated with these two categories are common to multiple regions, sectors, communities, and actors. Nevertheless, the manner in which they manifest is context-dependent (Adger *et al*., 2007; Kasperson and Berberian, 2011; Weichselgartner and Breviere, 2011; IPCC, 2012). Therefore, one must be cautious in applying generic assumptions regarding adaptation constraints in assessments of vulnerability and adaptive capacity or in the identification of appropriate adaptation responses(Adger and Barnett, 2009; Barnett and Campbell, 2009; Mortreux and Barnett, 2009). The recent adaptation literature suggests significant work remains in understanding such context-specific determinants of vulnerability and adaptive capacity (Tol and Yohe, 2007; Klein, 2009; Smith *et al*., 2010; Hinkel, 2011; Preston *et al*., 2011b) and in effectively using the diversity of knowledge gained from the multitude of available case studies to facilitate adaptation more broadly.

16.3.1. Constraints Affecting the Context for Adaptation

16.3.1.1. Framing of Adaptation

Adaptation processes are influenced by the manner in which individuals and institutions frame adaptation including the perception of climate change risks and the mental models employed to structure decision-making regarding adaptation (Nisbet and Scheufele, 2009; Fünfgeld and McEvoy, 2011; Preston and Mustelin, 2013) (see also 15.4.3.1). Framing elements include definitions of adaptation and to what actors must adapt; objectives and

responsibilities of actors; the role of knowledge; appropriate adaptation responses; and constraints and limits associated with implementation (Smith *et al*., 2000; Nelson *et al*., 2008; Meinke *et al*., 2009; Preston and Stafford Smith, 2009; Fünfgeld and McEvoy, 2011; Gifford, 2011; Klein and Juhola, 2013; Arbuckle Jr. *et al*., 2013; Preston and Mustelin, 2013). In particular, recent literature identifies risk perception as a constraint on adaptation by conveying over-confidence in the ability of actors to manage risk (Wolf *et al*., 2010; Kuruppu and Liverman, 2011) or creating differences in the perception of climate risk between actors and governing institutions (Patt and Schröter, 2008a). However, Whitmarsh (2008) finds that motivation for adaptation is mediated indirectly through individual, environmental values rather than direct perceptions of climate risk. Meanwhile, van der Berg *et al*. (2010) suggest local leadership and normative values may be more critical drivers of adaptation than risk perception. The inconsistency among such case studies suggests risk perception may interact with other factors to shape adaptation responses and/or that other factors take precedence. A number of authors have commented on the potential constraints associated with the framing of adaptation as strictly a top down (i.e., government-led) or bottom up (i.e., community-based) process. Orlove (2009), for example, notes that indigenous herders in Peru frame adaptation differently than those working within NGOs and government agencies. Hence, there may be value in more integrated views of risk governance (16.3.1.4).

Recent studies have also investigated the science/policy interface with respect to how vulnerability and adaptation assessment shape understanding of adaptation (Füssel and Klein, 2006b; McGray *et al*., 2007; McEvoy *et al*., 2010; Eakin and Patt, 2011; Fünfgeld and McEvoy, 2011; Jones and Preston, 2011; Preston *et al*., 2011b; Yuen *et al*., 2012). Concerns have been raised in the literature that assessment tools and paradigms such as climatic prediction, risk management, cost/benefit analysis may obfuscate the need for and desirability of alternative approaches to adaptation (O'Brien *et al*., 2007; Hulme *et al*., 2009a; Eriksen and Brown, 2011; Eriksen *et al*., 2011; Pelling, 2011). Eisenack and Stecker (2012) and Klein and Juhola (2013) comment on the disconnect between adaptation research and policy that arises from limited consideration for the role of actors in shaping adaptation responses. Meanwhile, multiple authors have raised questions regarding the utility and legitimacy of vulnerability metrics for prioritizing adaptation interventions (Klein, 2009; Hinkel, 2011; Preston *et al*., 2011b). Greater incorporation of actors and communities into assessment processes and education interventions may be a pathway for increasing their potential to trigger effective adaptation responses(Kuruppu and Liverman, 2011; Klein and Juhola, 2013).

16.3.1.2. Rates of Change

There is *high agreement, robust evidence* that future rates of global change will have a significant influence on the demand for and costs of adaptation. Since, the AR4, new research has confirmed the commitment of the Earth system to future warming (Lowe *et al*., 2009; Armour and Roe, 2011) and elucidated a broad range of tipping points or 'key vulnerabilities' in the Earth system that would result in significant adverse consequences should they be exceeded (Lenton *et al*., 2008; Rockstrom *et al*., 2009); Chapter 19). While the specific rate of climate change to which different ecological communities or individual species can adapt remains uncertain (16.5), there is high agreement, robust evidence that more rapid rates of change constrain adaptation of natural systems (Hoegh-Guldberg, 2008; Gilman *et al*., 2008; Maynard *et al*., 2008; Allen *et al*., 2009; Malhi *et al*., 2009a; Malhi *et al*., 2009b; Thackeray *et al*., 2010; Lemieux *et al*., 2011), particularly in the presence of other environmental pressures (Brook *et al*., 2008). Therefore, if greenhouse gas mitigation policy is unable to reduce the rate of climate change, the effectiveness of some adaptation options may be reduced and higher costs for adaptation may be incurred (New *et al*., 2011; Stafford Smith *et al*., 2011; Peters, G.P., Andrew, R.M. *et al*., 2013).

Meanwhile, although rapid socioeconomic change, including economic development and technological innovation and diffusion, can enhance adaptive capacity, they can also pose constraints to adaptation. Globally, rates of economic losses from climate extremes are doubling approximately every one to two decades due to increasing human exposure (Pielke Jr. *et al*., 2008; Baldassarre *et al*., 2010; Bouwer, 2011; Gall *et al*., 2011; Munich Re, 2011; IPCC, 2012). These trends in losses are projected to continue in future decades (Pielke Jr., 2007; Montgomery, 2008; O'Neill *et al*., 2010; UN, 2011; Preston, Submitted);10.7.3). In addition, population growth and economic development can lead to greater resource consumption and ecological degradation (Alberti, 2010; Chen *et al*., 2010; Raudsepp-Hearne *et al*., 2010; Liu *et al*., 2012), which can constrain adaptation in regions that are dependent on natural resources (Badjeck *et al*., 2010; Marshall, 2010; Warner *et al*., 2010); CC-EA). Global trends toward

population aging can increase vulnerability by increasing net population sensitivity to climate extremes (O'Brien *et al*., 2008; Wolf *et al*., 2010; Bambrick *et al*., 2011). The adaptation literature also suggests that successful adaptation will be dependent in part upon the rate at which institutions can learn to adjust to the challenges and risks posed by climate change and implement effective responses (Adger *et al*., 2009b; Moser and Ekstrom, 2010; Stafford Smith *et al*., 2011).

16.3.1.3. Social and Cultural Dimensions

Adaptation can be constrained by social and cultural factors that are based on societal ideals regarding how a society should function and what is valued (O'Brien, 2009; Moser and Ekstrom, 2010; O'Brien and Wolf, 2010; Hartzell-Nichols, 2011). These social and cultural factors are the normative dimension of adaptation (O'Brien, 2009) (O'Brien, 2009), which determines what kind of adaptation is considered useful and feasible as well as when and by whom (Grothmann and Patt, 2005; Weber, 2006; Patt and Schröter, 2008b; Kuruppu, 2009; Adger *et al*., 2009b; Nielsen and Reenberg, 2010; Wolf and Moser, 2011; Wolf *et al*., 2013). Gender roles and identity, traditionally acceptable livelihoods, caste or class, land ownership systems, and religion can influence adaptation processes and hinder adaptive actions at individual, household and community levels (Ahmed and Fajber, 2009; Bryan *et al*., 2009; Codjoe *et al*., 2011; Jones and Boyd, 2011). Yet, values are not homogenous across society, which results in differential preferences for adaptation that can contribute to societal conflict (Wolf *et al*., 2013). Women in particular are often constrained by cultural and institutional pressures that favor male land ownership (Jones and Boyd, 2011) and constrain access to hazard information (Ahmed and Fajber, 2009). The lack of perception of vulnerability has left for example elderly people unprepared for heat waves in the UK (Sheridan, 2007; Wolf *et al*., 2009). Meanwhile, evidence suggests that chronic stresses such as poverty affect cognition and behavior, which influence adaptive capacity (Dias-Ferreira *et al*., 2009; Spears, 2011). Cultural constraints also include lack of oral history of disasters and risks, a prominent phenomenon in developed countries where highly vulnerable environments are built upon without adequate understanding of the landscape and its history (Heyd and Brooks, 2009). Studies indicate that cultural preferences regarding the value of traditional versus more formal scientific forms of knowledge influences that types of knowledge are considered legitimate (Jones and Boyd, 2011) and thus the way in which knowledge is used in adaptation (Box 16-2). Furthermore, social constraints can arise from governance arrangements which, for example, in the Arctic constrain individual's and communities' hunting and fishing practices and adaptation opportunities (Loring *et al*., 2011); 16.4.2.3).

Perceptions of the need for adaptation are also shaped by religion and sense of place. Religious beliefs can constrain adaptation as they reduce the perceived necessity and opportunities for adaptation while contributing to increase in vulnerability. Such constraints have emerged, for example, through religious institutions that have placed extensive financial commitments on their members reducing available capital for adaptation (Kuruppu, 2009). In Kiribati, Zanzibar, Tibet, Ecuador, and Mozambique, natural hazards are viewed as events controlled by God, supernatural forces, or ancestral spirits about which nothing can be done (Schipper, 2008; Byg and Salick, 2009; Mustelin *et al*., 2010; Kuruppu and Liverman, 2011; Artur and Hilhorst, 2012). In Tuvalu, God is attributed responsibility to take care of the people (Mortreux and Barnett, 2009). Adger *et al*. (2011; 2012a) and Fresque-Baxter and Armitage (2012) argue that sense of place, tied intimately to identity, shapes adaptation responses through sense of belonging, security, social connections, self-esteem, and emotional attachment. For example, Park *et al*. (2011) note that sense of place attachment among wine grape growers in Australia precludes consideration for migration to other growing areas. Further ethnographic explorations are needed to better grasp how and to what extent global climatic processes alter culture, values, and identity (Crate, 2011). Improved understanding is also needed regarding how gender, religious beliefs, land-use and rights can decrease vulnerability and enable individual, household and community adaptation.

16.3.1.4. Governance and Institutional Arrangements

Governance and institutional arrangements may both enable adaptation and act as potential constraints. Decision-making regarding adaptation is often undertaken within a context of multi-level governance including governmental administration at local to international levels as well as market actors and non-governmental organizations

(Rosenau, 2005). As a result, coordination or interplay among actors is crucial for facilitating adaptation decision-making and implementation (Young, 2006; van Nieuwaal *et al*., 2009; Grothmann, 2011). While some attention has been given quite recently to role of the private sector in adaptation governance (CDP, 2012; Taylor *et al*., 2012; Tompkins and Eakin, 2012), adaptation research and practice to date has largely focused on the public components of governance, particularly formal government institutions. Studies of the development of adaptation planning and policy at different levels of governance largely center on case studies (van Nieuwaal *et al*., 2009; Hunt and Watkiss, 2011), often by issue or level of government (Gagnon-Lebrun and Agrawala, 2006; Swart *et al*., 2009; Corfee-Morlot *et al*., 2009; Keskitalo, 2010; Biesbroek *et al*., 2010; Ford and Berrang-Ford, 2011; Preston *et al*., 2011a).

Multi-level governance of adaptation is challenged by the different regulatory and legal systems – including differing levels of decentralization – that exist across different geopolitical scales as well as differential authorities and power relationships. The NRC (2009) argued that U.S. institutions across scales lack the mandate, information, and/or professional capacity to select and implement adaptations for risk reductions. Similarly, Zinn (2007) and Preston (2009) suggest that effective responses to climate change would require levels of integrated environmental planning and management that governance systems have not been able to achieve consistently. Adger *et al*. (2009b), attribute such deficiencies to the complexity of governance systems that pose challenges to coordinating adaptation efforts, due in part to different objectives among actors (Preston *et al*., 2013). Similarly, Birkmann *et al*. (2010) observe that many urban adaptation plans depend on the involvement and interplay of formal and informal organizations, but these plans rarely address how this integration might be achieved (also see Chapter 15 on implementation). As binding legislation at national and in some cases subnational levels may create disincentives or potentially limit adaptation even in cases where adaptation per se is not the focus of legislation, adaptation decision-making at local level is partly shaped by higher levels as well as by the distribution of authority within the state (Urwin and Jordan, 2008; Huntjens *et al*., 2010a; Measham *et al*., 2011; Pittock, 2011; Westerhoff *et al*., 2011; Mukheibir *et al*., 2012; Amaru and Chhetri, 2013). The literature notes the challenges of changing legal principles to accommodate more forward-looking adaptation responses (Craig, 2010; McDonald, 2011). Preston *et al*. (2013), for example, identify cases in Australia and the United States where state government policies have impeded local governments from anticipatory adaptation for sea-level rise. A study of adaptation policy initiatives in the UK, Sweden, Finland and Italy, concluded that while initiatives at the central government level may play a significant role in supporting the development of adaptation policies at the local level, in cases where there is limited top down leadership or prioritization on adaptation, less centralized state structures could allow opportunities for local initiatives (Keskitalo, 2010). Transnational governance also influences adaptive capacity. For instance, in some cases in the European Union, funding programs have enabled local action on adaptation even in the absence of funding from the relevant EU member state (Keskitalo, 2010). The need for adaptation thus creates new challenges for the complex multi-national and multi-level governance of resources, particularly where there are ongoing disputes or conflicts (16.3.5). New institutions and bridging organizations will be needed to facilitate integration of complex planning processes across scales (National Research Council, 2010).

16.3.1.5. Monitoring and Evaluation

The AR4 provided little discussion of the role of monitoring and evaluation (M&E) of adaptation responses as a component of building adaptive capacity. Nevertheless, adaptation guidance, such as the guidelines for the preparation of National Adaptation Programmes of Action (UNFCCC, 2002), the United Nations Development Programme's *Adaptation Policy Framework* (Lim *et al*., 2005), and a range of climate change risk management frameworks (Jones, 2001; Willows and Connell, 2003; NZCCO, 2004a; NZCCO, 2004b; AGO, 2006; USAID, 2007; World Bank, 2008) all emphasize the importance of M&E for adaptation planning and implementation. The UK's Adaptation Sub-Committee, for example, recommends the monitoring of the implementation of the National Adaptation Programme and several agencies already have M&E protocols in place to track the effectiveness of responses to climate-related risks (Adaptation Sub-Commitee, 2012). In particular, M&E enables practitioners to develop robust adaptation practice through learning from policy successes and failures (GIZ, 2011a; GIZ, 2011b). Nevertheless, the long time scales associated with climate change and adaptation responses as well as uncertainty about the future pose significant challenges for evaluating success (GIZ, 2011b), particularly when there is a lack of consensus with respect to adaptation objectives (de Franca Doria *et al*., 2009; Osbahr *et al*., 2010). The literature on participatory M&E may offer guidance for how to overcome such conflicts by enhancing the incorporation of tacit

and local knowledge into M&E and the prioritization of management interventions (Brown *et al*., 2012; Harvey *et al*., 2012; Stringer and Dougill, 2013). Recent evidence suggests guidance on climate adaptation M&E is increasingly being translated into practice (GIZ, 2011a; GIZ, 2011b). However, Preston *et al*. (2011a) argue that adaptation M&E is more advanced in the developing world due to the close linkages between adaptation and development assistance (Global Environmental Facility, 2006), which has a long history of M&E. In contrast, the limited evidence from developed nations suggests that many organizations have yet to engage on adaptation (Wheeler, 2008); have yet to turn adaptation planning into practice (Berrang-Ford *et al*., 2011; Ford *et al*., 2011); or are limiting adaptation actions to capacity building efforts (Preston *et al*., 2011a). Yet, the UK Climate Change Act (2008) and U.S. Executive Order 13514 (CEQ, 2011) contain reporting provisions with respect to adaptation planning and implementation. This suggests that the policy foundation for M&E in developed nations is emerging, but additional development of objectives, methods, and metrics for M&E may be required.

16.3.2. Constraints Affecting the Implementation of Adaptation Policies and Measures

The various socioeconomic processes that influence the context for adaptation ultimately influence the entitlements of actors to the capacity and resources needed to support the implementation of adaptation policies and measures (Figure 16-2). The literature on vulnerability and adaptive capacity, for example, has traditionally focused on the availability of such resources and differential availability and access across different sectors, regions, and actors (Jantarasami *et al*., 2010; Moser and Ekstrom, 2010). For example, multiple studies have assessed adaptive capacity in sectors and communities using sustainable livelihoods framework (Paavola, 2008; Osbahr *et al*., 2010; Nelson *et al*., 2010a; Nelson *et al*., 2010b), which deconstructs adaptive capacity into five types of capital: financial, physical, natural, social, and human. Hence, adaptation efforts can be constrained by various factors including knowledge regarding climate change and adaptation (Deressa *et al*., 2011); Box 16-2); availability of adaptation finance (Hof *et al*., 2009; Smith *et al*., 2009b; Barr *et al*., 2010; Schultz, 2012); degradation of natural resources (Humphreys *et al*., 2007; Paavola, 2008; Thornton *et al*., 2008; Iwasaki *et al*., 2009; Badjeck *et al*., 2010; Côté and Darling, 2010; Nkem *et al*., 2010; Tobey *et al*., 2010); effectiveness of technology (UNFCCC, 2006; Adger *et al*., 2007; Dryden-Cripton *et al*., 2007; van Aalst *et al*., 2008); the degree of public engagement in adaptation (van Aalst *et al*., 2008; Burton and Mustelin, 2013); and the quality of human capital and leadership (Ebi and Semenza, 2008; Termeer *et al*., 2012). Such constraints have been identified and discussed in previous IPCC reports (Adger *et al*., 2007; IPCC, 2012), and are closely aligned to the discussion of adaptation needs in Chapter 14. Therefore, this chapter focuses on providing illustrative examples from the literature of how such constraints affect adaptation implementation (Table 16-1) and synthesizing key constraints across the regional and sectoral chapters (16.5). However, debates appear within the adaptation literature regarding the extent to which some types of resources constrain adaptation (Box 16-2).

[INSERT TABLE 16-1 HERE
Table 16-1: Constraints affecting the implementation of adaptation policies and measures.]

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Box 16-2. Is Knowledge a Constraint on Adaptation?

The generation and dissemination of knowledge regarding climate change and adaptive responses are important components of adaptation processes and, in particular, the effective implementation of specific policies and measures. The various types of knowledge most frequently examined in adaptation studies include a) knowledge regarding future biophysical and socioeconomic conditions and associated uncertainties (Keller *et al*., 2008; Wilby *et al*., 2009; Moss *et al*., 2010); b) knowledge regarding adaptation options and their associated costs and benefits (Prato, 2008; de Bruin *et al*., 2009b; Patt *et al*., 2010a); and c) knowledge regarding the various constraints on, or limits to, the implementation of those options and how they can be ameliorated (Mitchell *et al*., 2006; Smith *et al*., 2008; Moser, 2009; Moser and Ekstrom, 2010; Conway and Schipper, 2011). Although the pursuit of adaptation has been linked to education and awareness of climate change among actors (Deressa *et al*., 2011), the adaptation literature reflects different perspectives on the manner in which knowledge constraints adaptation. Adaptation practitioners and stakeholders continue to identify a deficit of information as a major constraint on adaptation

(Adger *et al*., 2009b; Jones and Preston, 2011; Preston *et al*., 2011a). This is evidenced by surveys and case studies in both developed (Tribbia and Moser, 2008; Jantarasami *et al*., 2010; Gardner *et al*., 2010; Ford *et al*., 2011) and developing nations (Bryan *et al*., 2009; Deressa *et al*., 2009). Discussions of knowledge deficits in the literature are often closely associated with the broader issue of uncertainty and its implications for adaptation. Key sources of uncertainty include scientific understanding of biophysical processes that influence future climate change; understanding of socioeconomic processes that influence the impacts of, and responses to, climate change; and understanding of the costs and benefits of different adaptation policies (Congressional Budget Office, 2005; Fankhauser, 2009; Hallegatte, 2009b; Arnell, 2010; Patt *et al*., 2010a; UNFCCC, 2011). Nevertheless, the AR4 concluded that knowledge in itself is not sufficient to drive adaptive responses (Adger *et al*., 2007). Recent literature has questioned, for example, the extent to which uncertainty and/or lack of information about future climate change is a constraint on adaptation (Dessai *et al*., 2009; Hulme *et al*., 2009b; Wilby and Dessai, 2010), particularly over the near-term. Approaches such as robust decision-making and so-called 'no regrets' or 'win-win' strategies may identify adaptation options that are insensitive to uncertainty (Lempert and Collins, 2007; Hallegatte, 2009a; Adger *et al*., 2009b; Wilby and Dessai, 2010). Other authors have also questioned the utility of vulnerability metrics and assessments for informing adaptation decision-making (Barnett *et al*., 2009; Preston and Stafford Smith, 2009; Klein, 2009; Hinkel, 2011; Preston *et al*., 2011a).

Studies also indicate that the role of knowledge in adaptation is closely tied to culture. For example, cultural preferences regarding the value of traditional versus more formal scientific forms of knowledge influence what types of knowledge are considered legitimate (Jones and Boyd, 2011). In the Arctic, however, Inuit traditional knowledge (*Inuit Qaujimajatuqangit,* IQ) encompasses all aspects of traditional Inuit culture including values, world-view, language, life skills, perceptions and expectations (Nunavut Social Development Council, 1999; Wenzel, 2004). While declining especially among youth (Pearce *et al*., 2011), IQ includes, for example, weather forecasting, sea ice safety, navigation, hunting and animal preparation skills that link together Inuit perception, knowledge, and values and are essential for managing climate risk. On the other hand, evidence suggests that increasing reliance on non-traditional forecasting (national weather office forecasts) and other technologies (GPS) in Arctic communities is in part responsible for increased risk taking when travelling on the land and sea ice (Aporta and Higgs, 2005; Ford *et al*., 2006; Pearce *et al*., 2011). As a result, the implications of relying upon traditional forecasting and skills are place and context-dependent. These various studies, and the inconsistency of conclusions that arise, indicates that the extent to which knowledge acts to constrain or enable adaptation is ultimately dependent upon how that knowledge is generated, shared and used to achieve desired adaptation objectives (Patt *et al*., 2007; Nelson *et al*., 2008; Tribbia and Moser, 2008; Moser, 2010).

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16.3.3. Constraints across Spatial and Temporal Scales

Despite an emphasis in the adaptation literature on place-based adaptation, adaptation can be constrained by processes that transcend multiple spatial scales (Adger *et al*., 2005; Eakin and Wehbe, 2009; Preston and Stafford Smith, 2009; Adger *et al*., 2009a; Preston and Mustelin, 2013); 16.4.1.4). International efforts to reduce greenhouse gas emissions, for example, influence the magnitude and rate of change in climate at national, regional, and local scales (16.7). Adaptation constraints can also propagate from the bottom up. For example, global food commodity prices increased sharply in 2006–2008 and again in 2010–2011 due in part to the impacts of extreme weather events on food producing regions. The resulting increase in food prices benefited some producers in developed nations, but undermined food security in developing nations (FAO, 2011). Much of the literature on adaptation and spatial scales, however, focuses on climate impacts and adaptive responses that pose trans-boundary challenges, such as water resources management in multi-national or multi-state river basins (Iglesias *et al*., 2007; Goulden *et al*., 2009; Krysanova *et al*., 2010; Huntjens *et al*., 2010b; Timmerman *et al*., 2011; Wilby and Keenan, 2012).

Constraints on adaptation can also transcend temporal scales. Development of water management and allocation systems in both Australia and the U.S. Southeast occurred during periods of relatively favorable rainfall (Jones, 2010; Pederson *et al*., 2012), resulting in systems that have been challenged to cope with persistent drought in recent decades. Similarly, Libecap (2010) suggests that water infrastructure developed in the U.S. West in the late-19th and

early 20th centuries has resulted in path dependence that constrains management choice regarding water allocation in the present. Cherti *et al*. (2010) suggest similar challenges may exist for the U.S. agricultural industry in the future due to constraints on farmers' capacity to alter management practices and technology in response to a changing climate. Preston (Preston, Submitted) illustrates how the continuation of historical patterns of U.S. population growth and wealth accumulation will contribute to significant increases in future societal exposure to extreme events and associated economic losses. Attempts to rectify such path dependence come at significant costs. For example, the Australian Government has committed AUS$3.1 billion to purchase water entitlements in an attempt to restore water usage in the Murray Darling basin to sustainable levels (Commonwealth of Australia, 2010). Hence, the literature on flexible adaptation pathways emphasizes the implementation of reversible and flexible options (Stafford Smith *et al*., 2011; Haasnoot *et al*., In Press) as well as 'real options' that recognize that there may be value in delaying adaptation decisions until additional information is available (Dobes, 2008).

16.3.4. Constraints and Competing Values

Constraints on adaptation arise from the differential values of societal actors and the trade-offs associated with prioritizing and implementing adaptation objectives (Haddad, 2005; UNEP, 2011); Table 16-2). At international scales, for example, deliberation over how the adaptation needs of least developed countries will be financed has become central to the UNFCCC policy agenda (UNFCCC, 2007; Ayers and Huq, 2009; Dellink *et al*., 2009; Flåm and Skjærseth, 2009; Denton, 2010; Patt *et al*., 2010b). Yet the extent to which the developed world bears responsibility for compensating the developing world for climate impacts has been a contentious issue (Hartzell-Nichols, 2011). Brouwer *et al*., (2013) report that policy-makers in the EU may be reluctant to pursue climate adaptation, because such efforts may conflict with existing objectives with respect to maintain water quality. Even at local scales, Measham *et al*. (2011) report that some Local Government stakeholders in Australia find it difficult to pursue adaptation efforts to due perceived conflicts with an adaptation agenda with community values. Such differences among stakeholders with respect to the need for adaptation and appropriate adaptation responses may result in some actions being simultaneously perceived as adaptive and maladaptive (Bardsley and Hugo, 2010). Alternatively, whether an adaptation option represents an opportunity or a constraint may depend upon the manner in which it's implemented. Recognizing the potential for values conflicts to constrain adaptation, researchers and practitioners have advocated for so-called 'no regrets' or 'low regrets' adaptation strategies (Heltberg *et al*., 2009). However, Preston *et al*. (2011a) suggest such no regrets actions may reduce investments in more substantive adaptations necessary to protect highly vulnerable systems or avoid irreversible consequences. Meanwhile, Adger *et al*. (2009a) question whether incremental adaptation is sufficient to avoid consequences that directly impact human values and cultural identities that cannot be readily compensated. Addressing such risks through adaptation may necessitate deliberation among stakeholders regarding adaptation objectives and the manner in which competing or conflicting values can be reconciled to achieve outcomes (McNamara and Gibson, 2009; de Bruin *et al*., 2009b; McNamara *et al*., 2011; UNEP, 2011).

[INSERT TABLE 16-2 HERE
Table 16-2: Examples of potential trade-offs among adaptation objectives.]

16.3.5. Interactions among Constraints

Deconstruction of adaptation constraints into discrete factors assists with their identification and diagnosis, but, such constraints rarely act in isolation (Dryden-Cripton *et al*., 2007; Smith *et al*., 2008; Moser and Ekstrom, 2010; Shen *et al*., 2011); 16.4.6). Rather actors are challenged to navigate multiple, interactive constraints in order to achieve a given adaptation objective(Adger *et al*., 2007; Dryden-Cripton *et al*., 2007; Smith *et al*., 2008; Shen *et al*., 2008; Adger *et al*., 2009b; Jantarasami *et al*., 2010; Moser and Ekstrom, 2010; Shen *et al*., 2011). For example, while the cost of adaptation is frequently cited as a constraint on action, cost is a function of rates of climate change and greenhouse gas mitigation efforts (16.4.2.2), the availability of finance (16.4.1.3), and available technologies (16.4.1.4). Meanwhile, the perceived costs and benefits of a given adaptation option have strong intersections with governance as well as social and cultural preferences (Dryden-Cripton *et al*., 2007; Smith *et al*., 2009b; Engle, 2011; Shen *et al*., 2011). Multiple constraints can significantly reduce the range of adaptation options and opportunities

and therefore may pose fundamental limits to adaptation (16.5), and/or drive actors toward responses that may ultimately prove to be maladaptive (Barnett and O'Neill, 2010). As such, removing various constraints on adaptation, which in turn increases adaptation options and flexibility, is fundamental to the facilitation of adaptation processes (Smith *et al*., 2008; Moser and Ekstrom, 2010). Bottom up approaches have been credited with making adaptation constraints explicit and stimulating social learning (Preston *et al*., 2009; Yuen *et al*., 2012), but have yielded less evidence of substantive adaptation. Meanwhile, top down, index-based approaches have come under criticism due to concerns about robustness and relevance to adaptation decision-making (Hinkel, 2011; Preston *et al*., 2011a). Ongoing advances in comprehensive understanding of multiple, interacting constraints as well as the manner in which they influence adaptation and outcomes are needed to facilitate adaptation practice (Engle, 2011).

16.4. Limits to Adaptation

There is *high agreement and much evidence* that there are limits to the capacity of actors to adapt to climate change (Meze-Hausken, 2008; O'Brien, 2009; Adger *et al*., 2009b; Moser and Ekstrom, 2010; Dow *et al*., 2013); 16.4). Although constraints increase the challenges associated with implementing adaptation policies and measures, they do not necessarily pose a limit to adaptation in themselves. A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to the existing objectives and values and prevent the loss of the key attributes, components or services of ecosystems (see Box 16-1). There is a variety of circumstances and associated terminology in the literature that relate to adaptation limits including 'thresholds' (Meze-Hausken, 2008; Briske *et al*., 2010; Washington-Allen *et al*., 2010); 'regime shifts' (Washington-Allen *et al*., 2010); 'tipping points' (Lenton *et al*., 2008; Kriegler *et al*., 2008); 'dangerous climate change' (Mastrandrea and Schneider, 2004; Ford, 2009a); 'reasons for concern' (Smith *et al*., 2009a); 'planetary boundaries' (Rockstrom *et al*., 2009); or 'key vulnerabilities' (Schneider *et al*., 2007; Johannessen and Miles, 2011; Hare *et al*., 2011); Chapter 19). In addition, terms such as barriers, limits, and constraints are sometimes used interchangeably. Due to this diversity in language, this discussion builds on recent efforts to develop a common lexicon to facilitate research and practice (Hulme *et al*., 2007; Adger *et al*., 2009b; Dow *et al*., 2013; Dow *et al*., In Press); 16.2; Box 16-1).

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Box 16-3. Historical Perspectives on Approaching and Exceeding Limits to Adaptation

Does human history provide insights into societal resilience and vulnerability under conditions of environmental change? Archeological and environmental reconstruction provides useful perspectives on the role of environmental change in cases of significant societal change (sometimes termed 'collapse' (Diamond, 2005)). These may help to illuminate how adaptation limits were either exceeded, or where this was avoided to a greater or lesser degree. Great care is necessary to avoid over-simplifying cause and effect, or over-emphasizing the role of environmental change, in triggering significant societal change, and the societal response itself. Coincidence does not demonstrate causality, such as in the instance of matching climatic events with social crises through the use of simple statistical tests (Zhang *et al*., 2011), or through derivative compilations of historical data (deMenocal, 2001; Thompson *et al*., 2002; Drysdale *et al*., 2006; Butzer, 2012). Application of social theories may not explain specific cases of human behavior and community decision-making, especially because of the singular importance of the roles of leaders, elites and ideology (Hunt, 2007; McAnany and Yoffee, 2010; Butzer and Endfield, 2012; Butzer, 2012).

There are now roughly a dozen case studies of historical societies under stress, from different time ranges and several parts of the world, that are sufficiently detailed (based on field, archival, or other primary sources) for relevant analysis (Butzer and Endfield, 2012). These include Medieval Greenland and Iceland (Dugmore *et al*., 2012; Streeter *et al*., 2012); Ancient Egypt (Butzer, 2012); Colonial Cyprus (Harris, 2012); the prehistoric Levant (Rosen and Rivera-Collazo, 2012); Islamic Mesopotamia and Ethiopia (Butzer, 2012); the Classic Maya (Dunning *et al*., 2012; Luzzadder-Beach *et al*., 2012); and Colonial Mexico (Endfield, 2012). Seven such civilizations underwent drastic transformation in the wake of multiple inputs, triggers, and feedbacks, with unpredictable outcomes. These can be seen to have exceeded adaptation limits. Five other examples showed successful adaptation through the interplay of environmental, political and socio-cultural resilience, which responded to multiple stressors (e.g., insecurity, environmental or economic crises, epidemics, famine). Climatic perturbations are identified as only one

of many 'triggers' of potential crisis, with preconditions necessary for such triggers to stimulate transformational change. These preconditions include human-induced environmental decline mainly through over-exploitation. Avoidance of limits to adaptation requires buffering feedbacks that encompass social and environmental resilience. Exceedance of limits occurred through cascading feedbacks that were characterized by social polarization and conflict that ultimately result in societal disruption. Political simplification undermined traditional structures of authority to favor militarism, while breakdown was accompanied or followed by demographic decline. Although climatic perturbations did contribute to triggering many cases of breakdown, the most prominent driver at an early stage was institutional failure. Environmental degradation seldom played a pivotal role. Collapse was neither abrupt nor inevitable, often playing out over centuries.

These historical insights cannot be directly applied to contemporary problems of sustainability without adjustment for cumulative information and evolving developments such as increasing social possibilities for grassroots participation. For example, from the 14th to 18th centuries AD, Western Europe responded to environmental crises at great societal cost, with high nutritional stress and long-wave demographic fluctuations. This occurred through the consideration of traditional knowledge and the localized evaluation of new information to emphasize innovation, experimentation and intensification, sometimes under the stress of fresh environmental perturbations or social unrest. Resilience and adaptation depended on experience, communications, identification of alternative options, and a measure of consensus. Effective change in recent historical societies involved both the grassroots and the elites, with the key questions increasingly cybernetic, structural, and cultural.

Recent work on resilience and adaptation synthesizes lessons from extreme event impacts and responses in Australia (Kiem *et al*., 2010). This further emphasizes an institutional basis for resilience, finding that government intervention through the provision of frameworks to enable adaptation is beneficial. Furthermore, it was found that a strong government role may be necessary to absorb a portion of the costs associated with natural disasters. On the other hand, community awareness and recognition of novel conditions were also found to be critical elements of effective responses.

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16.4.1. Hard versus Soft Limits

Although limits to adaptation are at times described in the literature as fixed thresholds(Adger *et al*., 2009b), recent studies have emphasized the need to consider the perspective of actors in defining adaptation limits (Adger *et al*., 2009b; Dow *et al*., 2013; Dow *et al*., In Press) as well as the dynamic nature of both biophysical and socioeconomic processes that influence adaptation decision-making and implementation (Dow *et al*., 2013; Dow *et al*., In Press). Informed by the distinctions drawn in the work of Meze-Hausken (2008), Adger *et al*. (2009b), and Moser and Eckstrom (2010), one can distinguish between "hard" limits, those that will not change, and "soft" limits, which could change over time. For human actors, whether a limit is hard or soft is usefully evaluated with respect to whether the capacity to implement an adaptation response to manage an intolerable risk could emerge in the future, even if that capacity is not immediately available in the present. For natural ecosystems, whether a limit is hard or soft is defined by the rate and capacity of species and ecosystem responses relative to environmental changes (Shaw and Etterson, 2012).

Discussions of hard limits in the literature are often associated with thresholds in physical systems that, if exceeded, would lead to irreversible changes or the loss of critical structure or function (Lenton *et al*., 2008; Adger *et al*., 2009b; IPCC, 2012; Preston *et al*., 2013). Such limits arise from the magnitude and/or rate of climate change (16.3.1.2). For example, a number of physical thresholds in the Earth system have been proposed as posing potential limits to adaptation, particularly large-scale events such as irreversible melting of the Greenland or Antarctic Ice Sheets, or collapse of the Atlantic Thermohaline Circulation (Schneider and Lane, 2006; Sheehan *et al*., 2008; Travis, 2010). Such physical thresholds, however, though relevant to understanding adaptation limits, are not necessarily limits in themselves as they neglect consideration for the adaptive capacity of natural and human systems(Leary *et al*., 2009; Adger *et al*., 2009b; Dow *et al*., 2013; Klein and Juhola, 2013; Preston *et al*., 2013; Dow *et al*., In Press).

For species and ecosystems, hard limits to adaptation are often associated with exceedances of the physiological capacity of individual organisms or communities to adapt to changes in the climate (i.e., temperature, rainfall, and/or disturbance regimes; (Peck *et al*., 2009)) or to climate-induced changes in the abiotic environment (e.g., ocean circulation and stratification, (Harley *et al*., 2006; Doney *et al*., 2012)). Such systems tend to be those that persist at the upper limit of climate tolerances (Sheehan *et al*., 2008; Dirnböck *et al*., 2011; Benito *et al*., 2011); those for which sustainability is closely tied to vulnerable physical systems (Johannessen and Miles, 2011); or those that are under significant pressure from non-climatic forces (Jenkins *et al*., 2011). For example, many species, including humans (Sherwood and Huber, 2010) and key food crops (e.g., wheat, maize, and rice) are known to have thermal limits to survival (IPCC, 2007a). Similarly, increased ocean acidity is expected to reduce the ability of some marine organisms, such as corals, to grow posing threats of significant ecosystem damage (CC-OA; CC-CR). However, even for unmanaged ecological systems, where there is robust evidence that limits exist, defining those limits remains challenging due to system complexity and lack of information regarding responses across different scales of biological organization (Steffen *et al*., 2009; Wookey *et al*., 2009; Lavergne *et al*., 2010; Preston *et al*., 2013). Furthermore, species have mechanisms for coping with climate change including phenotypic plasticity (Charmantier *et al*., 2008; Matesanz *et al*., 2010) genetic (evolutionary) responses (Gienapp *et al*., 17; Bradshaw and Holzapfel, 2006; Visser, 2008; Wang *et al*., 2013), and range shifts (Colwell *et al*., 2008; Thomas, 2010; Chen *et al*., 2011). Such mechanisms influence adaptation limits by extending the range of climate conditions with which individual organisms can cope in situ and/or enabling species to migrate over time to more suitable climates. Recent evidence suggests that range shifts and phenotypic plasticity, rather than evolutionary adaptation, may be a more common response to climate change (Merilä, 2012). Yet, more comprehensive assessments of such adaptive mechanisms are needed to develop robust understanding of ecological limits.

In contrast, limits within social systems are often soft as they are influenced by exogenous climate change as well as endogenous processes such as societal choices and preferences (Adger *et al*., 2009b). Various authors have noted that adaptation limits are socially-constructed by human agency in that economics, technology, infrastructure, laws and regulations, or broader social and cultural considerations can limit adaptation (Flåm and Skjærseth, 2009; O'Brien, 2009; Adger *et al*., 2009b; de Bruin *et al*., 2009b; Wilbanks and Kates, 2010; McNamara *et al*., 2011; Morrison and PICKERING, 2012). All of these factors, however, are dynamic and change over time. The Shared Socioeconomic Pathways, for example reflect different perspectives on future changes in the capacity of actors to adapt (Kriegler *et al*., 2012). Given rising incomes and advances in knowledge and technology, a greater number of adaptation options may become available to a greater number of actors over time. In contrast, impediments to development, constraints on investments in adaptation, or rapid escalations in risk may create more challenges for adaptation. Societal assessments of risk and willingness to invest in risk management are subject to many influences, such as experience of a recent disaster, some of which can result in rapid changes (Ho *et al*., 2008; Breakwell, 2010; Renn, 2011). Hence, Adger *et al*. (2009b; pg. 338), argue that many limits to adaptation are dependent on the changing goals, values, risk tolerances and social choices of society which may make them "*mutable, subjective, and socially constructed*." Similarly, Meze- Hausken (2008) views adaptation as being triggered in part by subjective thresholds including perceptions of change; choices, needs, and values; and expectations about the future (see also O'Brien, 2009). The influence of cognitive factors, culture, and ideology on judgments about risk is a well-documented element of risk management (Renn, 2008; IPCC, 2012); 14.3.1.1). Cost-benefit analyses and associated discount rates, for example, reflect a social value on investment returns (17.3.7.2). Yet, Morgan (2011) notes that adaptation planning based on cost-benefit analysis can pose limits to adaptation by discounting the future economic benefits of adaptation actions and excluding non-market benefits. Meanwhile, increasing loss and damage from societal exposure and climate change may pose economic limits to the insurability of disaster risks (10.7.3), which ultimately influences what activities can occur in certain locations.

Limits also have scale-dependent properties. A local community may not have the necessary resources to adapt but these constraints may be overcome by drawing in resources from regional, national, or international authorities as well as from NGOs. Adaptation finance and capacity building activities more broadly, for example, enable resources for adaptation to be transferred from developed nations to developing nations in order to overcome soft limits to adaptation. Nevertheless, the demand for adaptation finance is significantly larger than the current availability of resources represented through international adaptation funds (Flåm and Skjærseth, 2009; Hof *et al*., 2009), and there are challenges associated with developing a framework for the equitable and effective allocation of adaptation funds

(Barr *et al*., 2010; Smith *et al*., 2009b). Scale-dependence also manifests among different actors within sectoral supply chains. For example, climate change that poses limits to the sustainability of an individual farm enterprise may have little impact on a national or international agribusiness (Park *et al*., 2011). Such scale dynamics invariably arise within any complex networked system (e.g., energy, water resources, health), and they create inequities among actors with respect to who encounters limits and when.

When all options for managing a risk are exhausted, shifting or removing a soft limit can only occur through granting actors new entitlements to resources or technology (16.3.2); reform to governance systems and policies (16.3.1.4); and/or changes in values and risk tolerance (16.3.1.3). While some changes, such as global economic development, will occur autonomously, other changes are a function of social processes and human choice. In some instances, limits may arise from humans explicitly avoiding what would seem to be adaptive behaviors. Different communities and populations, for example, have different attitudes toward migration as a response to climate vulnerability (Acosta-Michlik and Espaldon, 2008; Locke, 2009; Mortreux and Barnett, 2009; Ford, 2009b). Yet, for some locations, such as low-lying islands in Torres Strait, adaptation in place is not a feasible option (Green *et al*., 2009), and thus sea-level rise poses a hard limit to those who view relocation as an intolerable risk. Foresight (2011) observes that staying in place when security continues to deteriorate can reflect a profound inability to pursue more positive adaptive options, which may be as significant a policy concern as migration. Therefore, while limits to adaptation may be soft in principle, in practice they can pose highly persistent obstacles to adaptation if the necessary societal changes to remove the limit are not forthcoming.

16.4.2. Limits and Transformational Adaptation

Adaptation has traditionally been viewed as a process of incremental adjustments to climate variability and change to maintain existing objectives and values (Burton *et al*., 2001). Reliance upon incremental adaptation, however, can create path dependence that ultimately leads to adaptation limits (Folke, 2006; Gallopin, 2006; Nelson *et al*., 2010; Pelling and Manuel-Navarrete, 2011).Once this point is reached, continuing to maintain those objectives and values can prove maladaptive resulting in chronic system underperformance or, in more severe instances, irreversible losses and system collapse (Box 16-3). Encountering an adaptation limit, however, does not necessarily result in the end of the adaptive process.Since the AR4, the adaptation and resilience literature has suggested that climate change may drive actors toward transformational changes (Dow *et al*., 2013), which include scaling-up of management efforts; introduction of new technologies or practices; geographic shifts in the location of activities, or fundamental changes in underlying objectives and values governing human and natural systems (Pelling, 2011; Stafford Smith *et al*., 2011; Kates *et al*., 2012; O'Neill *et al*., 2012; Park *et al*., 2012; 20.3). While transformational change is one pathway by which soft limits can be removed (16.4.1), they are also a means of adapting to hard limits. For example, transformation may involve accepting the loss of lower-order objectives (e.g., protection of existing vulnerable coastal property, or continuation of an agricultural practice in a given location) in order to continue to meet higher order objectives (e.g., resilient coastal communities or sustainable rural economies) (Pelling and Manuel-Navarrete, 2011). This suggests there are hierarchies of limits within systems (Park *et al*., 2012).Transformational adaptation, however, isn't without risks (Orlove, 2009; Kates *et al*., 2012), such changes can involve significant transaction costs and there are inherent uncertainties associated with the timing and magnitude of investment returns. Hence, the factors that constrain incremental adaptation also constrain transformation, but the greater scale of investment and/or shift in fundamental values and expectations required for transformational change may create greater resistance. Yet, the question of whether or not an adaptive response is in fact transformational is dependent how it is perceived by actors. Following on Davies and Hossain (1997), Preston and Stafford Smith (2009) argue that the feasibility of transformational change may be dependent upon whether it is perceived as a positive outcome (e.g., expansion of an industry into new locations; Park *et al*., 2012) or a negative (e.g., retreat from vulnerable locations; Kates *et al*., 2012).

16.4.3. Effects of Mitigation on Adaptation Constraints and Limits

Klein *et al*. (2007) in IPCC AR4 identified four ways in which adaptation and mitigation can inter- relate, one of which are mitigation actions that have consequences for adaptation. It follows that mitigation actions could have

consequences for adaptation constraints and limits. This section discusses the effects of alternative mitigation pathways on adaptation potential.

Klein *et al*. (2007) concluded that without mitigation, a magnitude of climate change may be reached that makes adaptation impossible for some natural systems, while for most human systems it would involve very high social and economic costs (see also Chapter 19). However, the literature aiming to establish at which magnitude of climate change, or at which levels of mitigation, such adaptation constraints and limits emerge, is scattered and inconclusive. Uncertainty about the location of both hard and soft limits is to a large extent due to the fact that these limits are determined not only by the degree and rate of climate change (and are therefore a function of mitigation pathways), but also by the degree and rate of non-climatic stresses affecting the resilience or adaptive capacity of natural and human systems. Little empirical information is available on the functional relationships between climate change, non-climatic stresses and the emergence of limits to adaptation, offering scant support to the idea that the 2°C global goal represents a limit.

Analysis by Christensen *et al*. (2011) shows that all emission scenarios – whether aggressive mitigation scenarios consistent with a 2°C stabilization pathway or medium-high emission scenarios such as SRES A1B or A1Fi – are very similar in terms of projected climate up to 2040. The effects of mitigation on overall adaptation potential will therefore arise in the medium to long term. Integrated assessment models (IAMs) can assess the relative damage-reducing effect of mitigation and adaptation, but in doing so these models assume the two strategies to be substitutes. However, mitigation and adaptation create benefits on different spatial, institutional and temporal scales and involve different actors with different interests. At the global level it requires the reconciliation of welfare impacts on people living in different places and at different points in time into a global aggregate measure of well-being. As highlighted in Chapter 17, defining the costs and benefits of adaptation is particularly difficult, limited by data, and depends on value judgments.

Furthermore, since AR4 the literature on tipping elements (Lenton *et al*., 2008; Kriegler *et al*., 2009; Levermann *et al*., 2012) has provided a greater separation of mitigation and adaptation, because only mitigation can avoid these discontinuities. These concerns have also been picked up in the economic literature, notably in relation to the plausible, if unknown, probability of catastrophic climate change (Weitzman, 2009) and 'fat tails', where uncertainty is so large that the tails of the probability distribution tend to dominate. Against this background, mitigation insures against catastrophic climate change, and thus mitigation has an additional objective to adaptation. While there could be potential for mitigation and adaptation substitutability under scenarios where catastrophic climate change is avoided, the thresholds for the onset of any tipping elements are not known.

[INSERT FIGURE 16-3 HERE]
Figure 16-3. Adaptation policy space as a function of mitigation pathways (Watkiss *et al*., 2013).]

Nonetheless, several studies using IAMs have investigated tradeoffs between mitigation and adaptation (De Bruin *et al*., 2009; Bosello *et al*., 2010), treating the two strategies as substitutes in order to find a balance or even an optimal mix. De Bruin *et al*. (2009) report that short-term optimal policies need to consist of a mixture of substantial investments in adaptation measures, coupled with investments in mitigation, even though the latter will only decrease damages in the longer term. They also find that the relative mix of the two depends critically on the assumptions, notably in relation to the discount rate and the parameterization of damages.

Such findings are preliminary, because the representation of adaptation in IAMs is very simple (Ackerman *et al*., 2009; Patt *et al*., 2010): the models adopt a highly aggregated and theoretical approach without considering any real-world constraints on adaptation. They also often assume perfect foresight, no uncertainty and no maladaptation (see also Watkiss, 2011; Berkhout, 2012). More recent models have attempted to address some of these issues. The PAGE09 model (Hope, 2011), for example, has less positive assumptions about adaptation than PAGE02 (assuming it to be about half as effective), which along with other factors leads to a strong increase in the economic costs of climate change.

16.5. Sectoral and Regional Syntheses of Adaptation Opportunities, Constraints, and Limits

THIS SECTION SYNTHESIZES MATERIAL AVAILABLE AT THE TIME OF WRITING FROM SECTORAL AND REGIONAL FIRST-ORDER DRAFTS – UPDATES WILL BE MADE WITH SUBSEQUENT INTERATIONS OF THOSE CHAPTERS

The adaptation literature since the AR4 reflects *high agreement and much evidence* that adaptation efforts can and will be constrained by multiple factors (16.3), and, in some cases, such constraints may effectively limit adaptation (16.4). However, there is also *high agreement and much evidence* that opportunities, constraints, and limits for adaptation vary significantly among different sectors and regional contexts (Adger *et al*., 2007). This heterogeneity arises from a range of sources including regional differences with respect to the rate and magnitude of climate change that is experienced, differential exposure and sensitivity of sectors or ecological systems, and differential capacity to adapt. In particular, a robust funding from the literature is the differential adaptive capacity of developed versus developing nations (Adger *et al*., 2007). Nevertheless, while developing nations face potential challenges for adaptation arising from development and adaptation deficits (2.3.2.2.; 15.4.3.1.; 15.6), challenges for adaptation planning and implementation have been reported for developed countries as well (NRC, 2009, 2010; Berrang-Ford *et al*., 2011; Preston *et al*., 2011a). Given this diversity in adaptation opportunities, constraints, and limits, it is important that they be considered in the specific context in which they arise. Therefore, this section draws on the various assessments of adaptation presented in the sectoral (Chapters 3-13) and regional (Chapters 22-30) chapters of the Working Group II report to synthesize knowledge regarding opportunities, constraints, and limits across these contexts.

16.5.1. Sectoral Synthesis

Each of the sectoral chapters in the Working Group II report addresses the opportunities for, and challenges associated with, the pursuit of adaptation (Table 16-3). Collectively, this represents a rich body of knowledge regarding understanding of adaptation processes and how they are evolving among different human and natural systems. Although each sectoral chapter assesses the relevant literature on adaptation somewhat independently, a common emphasis among these chapters is a need for integrated approaches to adaptation planning and implementation. For example, Integrated Water Resource Management (IWRM), Integrated Coastal Zone Management (ICZM), Community-Based Adaptation, and Ecosystem-Based Adaptation (CC-EA) are identified as cross-sectoral adaptation options, which are viewed as more effective than standalone efforts to reduce climate-related risks(Bijlsma *et al*., 1996); 3.6; 5.9). Such integration is important as many sectors experience threats not from by climate change, but also from a range of existing or emerging threats. The sectoral chapters also reflect the distinction between autonomous adaptation, which is particularly important for natural systems such as freshwater, terrestrial, and ocean ecosystems, and planned adaptation, which features strongly in the literature associated with human systems. Common constraints arise among different sectors, which resemble those addressed previously (16.3). These include institutional challenges, barriers to accessing resources for adaptation, as well as lack of or uncertain information (3.6.1). As such, many chapters emphasize the various opportunities for building capacity through development and increasing resilience to climate change by addressing other stresses to human and natural systems. While the sectoral chapters offer few explicit definitions of adaptation limits, they reflect the potential for soft limits to arise and the potential for them to be persistent due to interactions among multiple constraints (16.3.5). Meanwhile, the sustainability of individual species or ecosystems may experience hard limits in a change climate, as may ecosystem services for humans such as food crops and fisheries.

[INSERT TABLE 16-3 HERE
Table 16-3: Sectoral synthesis.]

16.5.2. Regional Synthesis

While the regional chapters assess the relevant literature on key sectors affected by climate change, those discussions are specific to the various regional contexts (Table 16-4). Mainstreaming climate change into national

development policies as well as regional and local planning and economic development has emerged as a unified theme across regions for addressing multiple, interacting, stresses (Dovers and Hezri, 2010; Tompkins *et al*., 2010). Most regional chapters reveal there is a significant mismatch between national adaptation planning on adaptation and local implementation to achieve substantive reductions in vulnerability. Just as there is a scale disconnect in adaptation planning and implementation, there is also a temporal disconnect. Adaptation interventions largely emphasize short-term risk management over long-term strategic planning, which potentially increases vulnerability and therefore the costs associated with future adaption efforts. Such short-sighted decision-making can also create the potential for maladaptation (Berrang-Ford *et al*., 2011). The regional chapters also reveal the fundamental disparities between developing and developed nations with respect to adaptive capacity. For example, Asia, Central and South America, and Africa reveal consistent weaknesses with respect to information on climate change and adaptation, access to other resources, and effective institutions for facilitating adaptation planning and implementation. Nevertheless, governance frameworks for incorporating adaptation are also identified in global regions such as North America and Europe, which are largely comprised of developed nations. A shift to risk-based approaches to adaptation offer opportunities for the development of approaches, tool and guidelines for the construction of adaptation plans with a long-term focus (16.7.2). In addition, ecosystem based adaptation (CC-EA) appears as another one adaptation opportunity to address short and long-term adaptation vulnerabilities in several regions (Africa, Australasia, Central and South America) (CC-EA).

[INSERT TABLE 16-4 HERE
Table 16-4: Regional synthesis.]

16.6. Ethical Dimensions of Adaptation Constraints and Limits

Hartzell-Nichols (2011, pg. 690) argues that "*Adaptation is fundamentally an ethical issue because the aim of adaptation is to protect that which we value*." This underlines the ethical dimensions of the framing of adaptation opportunities, constraints and limits adopted in this chapter as being concerned with risks to social objectives and values, and to needs of biophysical systems. However, defining what these values are and untangling the ethical issues is not straightforward. Defining general moral principles to clarify how to handle risks to objectives, values and needs, including where they are unavoidable and catastrophic, is difficult. According to Gardiner (2006, pg. 407), "*Even our best theories face basic and often severe difficulties addressing basic issues … such as scientific uncertainty, intergenerational equity, contingent persons, nonhuman animals, and nature. But climate change involves all of these matters and more"*. Complicating this picture further is the observation that social and personal values are not universal and nor are they static (O'Brien, 2009; O'Brien and Wolf, 2010). There may be different, equally well-founded values about an activity or value that is being put at risk by climate change. These are not limited to economic values, but include intangible cultural or spiritual values as well. Berkes (2008; pg. 163) documents that in Inuit culture, the loss of sea ice in summer months leaves some people 'lonely for the ice.' Whether the risk of such an irreversible cultural loss would be seen as intolerable remains a complicated question. The loss of traditional cosmologies and ways of seeing the world is a common occurrence throughout history. The ethical question is whether such non-material losses need to be acknowledged and whether there is a right to restitution.

One ethical principle that is widely applied in ethical discussions of climate is 'equity' (Gardiner, 2010). It is now well-established that nations, peoples and ecosystems are differentially vulnerable to current and future projected climate change impacts, which themselves are also almost certain to be unequally distributed across the world (IPCC, 2007b; Füssel, 2009; Füssel, 2010). This inequity is exacerbated by the fact that exposure to adverse impacts is involuntary for many societies (Paavola and Adger, 2006; Patz *et al*., 2007; Dellink *et al*., 2009; Füssel, 2010). Therefore, adaptation capacity and implementation constraints have the potential to create or exacerbate inequitable consequences due to climate change (*high agreement, robust evidence*). Linked to this is the complex question of the attribution of risks to anthropogenic forcing of climate change and whether there could be grounds for redress or compensation (Verheyen, 2005). Where limits to adaptation lead to catastrophic losses there are may be a strong need for humanitarian responses.

Inequity resulting from adaptation constraints and limits emerge across several dimensions; namely inter-country equity, inter-generational equity, inter-species equity (Schneider and Lane, 2005), and intra-country or sub-national equity (Thomas and Twyman, 2005). Adger *et al.* (2009b) propose that adaptation limits are endogenous to society and thus dependent on ethics, knowledge, attitudes to risk and culture. Inter-generational equity considerations are dominated by complex technical discussions about the time discount rate (Nordhaus, 2001; Stern *et al.*, 2006; Beckerman and Hepburn, 2007). This debate largely ignores the challenge of irreversible damages associated with limits to adaptation, especially those that may result from non-linear damage functions (Hanemann, 2008).

Inter-species equity is a complex topic and still the subject of evolving ethics unrelated to climate change considerations – value to human society increasingly serves as the most common metric for determining interventions affecting species (Balmford *et al.*, 2002). Clearly, differential ecosystem vulnerability is an important determinant of most species' vulnerability to climate change, with some species and ecosystems already severely threatened (IPCC, 2007b). Support for climate change adaptation interventions for species increasingly invokes human and societal benefits as a primary motivation (CBD, 2009).

Law codifies principles, norms and procedures for dealing with problems of risk and loss, including intolerable losses. National and international law will play a role in managing and sharing climate-related risks. The complexity of international law comprises a significant barrier to making the case for addressing the breaching of adaptation limits (Koivurova, 2007). At national and sub-national levels, cultural attitudes can contribute to stakeholder marginalization from adaptation processes, thus preventing some constraints and limits from being identified (such as gender issues and patriarchal conventions).

16.6.1. Ethics and the Externalities of Adaptation

There is a wide variety of potential positive and negative externalities associated with adaptation to climate change, and some of these have relevance in the context of constraints and limits. Externalities are important because they may allow 'free-riding' on the one hand, or, on the other hand, unintended adverse consequences that are not considered in implementing adaptation actions. Positive externalities can be projected at all levels of scale from international to local. Positive externalities may be associated with investments in public goods, but they may also arise from private investments in adaptation. Investments in health, food security and disaster risk reduction adaptive strategies may benefit neighbors most through reducing risks of social instability and resource demands. Negative externalities relate to adaptive strategies that reduce resource availability to neighbors, such as through water security strategies that may reduce availability to downstream neighbors (Eckstein, 2009), or generate new risks to neighbors, such as changing downstream flood risks as a result of raising river levees (te Linde *et al.*, 2011).

Positive distributional spill-overs of adaptation that aim to avoid limits are many and would benefit society through their monetization (Jack *et al.*, 2008). An example is the enhancement of ecosystem functions for local adaptation benefits (*e.g.,* restoration of wetlands to avoid the permanent loss of ecosystem services such as food and water security). The downstream externalized benefits would include a reduction in flood risk. Emerging concepts in the form of payments for ecosystem services would internalize these and provide further motivation for more integrated and equitable sharing of the burden and benefits of adaptation, but their implementation faces constraints relating to valuation and verification. There are few agreed international procedural arrangements for addressing or resolving these externalities, compounded by complex international law (Koivurova, 2007).

16.6.2. Ethics at the Limits of Adaptation

Historical reconstructions of societies that approach limits to adaptation involving a climate driver show that endogenous capabilities may determine whether limits are exceeded or avoided (Box 16-3). Ethical considerations are central to these endogenous responses. As real or perceived national or local limits to adaptation are approached, strategies may be encouraged that deprive neighbors of resources (FAO, 2011). Adaptation to water resource limitations may be particularly pernicious (Eckstein, 2009), with local strategies involving water table reductions that affect entire regions, and national strategies that impound water that would have previously flowed between or

across political boundaries. Intergenerational concerns are important for considering the ethics relating to avoiding adaptation limits. This is because several generations in the twenty-first century, at least, will experience progressively changing climates (Adger *et al*., 2009b), which could expose them to greater probabilities of exceeding adaptation limits.

16.7. Seizing Opportunities, Overcoming Constraints, and Avoiding Limits

16.7.1. Opportunities for Adaptation

We take adaptation opportunities to be factors that make it easier to plan and implement adaptive actions, or which ease adaptive responses to climate-related risks in ecosystems. An opportunity is distinct from an adaptation option, which is a specific means of achieving a social adaptation objective (such as an early warning system as a means of reducing vulnerability to tropical cyclones) or a strategy for securing a key ecological attribute (see Chapter 14.3.2 for discussion).We also do not consider here potential benefits of climate change, an issue addressed to varying degrees among the various sectoral and regional chapters.

Previous literature has focused especially on opportunities (and constraints) to build adaptive capacity and adaptation in national (Tompkins *et al*., 2010) and international policy contexts, while tending to neglect the important role of the private sector in facilitating adaptation (Tompkins and Eakin, 2012). The AR4 argues that public policy has a growing role in reducing vulnerability of people and infrastructure, providing information on risks for private and public investments and decision-making, and protecting public goods such as habitats, species and culturally important resources (Adger *et al*., 2007). Such roles include research and innovation support for adaptation options, creating the enabling environment for adaptation options to be implemented and ensuring that spillovers and externalities associated with adaptation options are managed. In a similar vein, the IPCC SREX report argues that (IPCC, 2012b: pg. 9),

> *"National systems are at the core of countries' capacity to meet the challenges of observed and projected trends in exposure, vulnerability, and weather and climate extremes. Effective national systems comprise multiple actors from national and sub-national governments, the private sector, research bodies, and civil society including community-based organizations, playing differential but complementary roles to manage risk, according to their accepted functions and capacities."*

In relation to ecosystem resilience, there is also a clear role for public policy (Vignola *et al*., 2009). Here too, common themes include information, mainstreaming, dialogue and participation. Special emphasis is placed on the transfer of power to local communities for adaptation decision-making. Given the great variability in social and ecosystem resilience, and the importance of local conditions and capacities in responding to these climate-related risks, there is often a rationale for local governance of adaptation. On the other hand, local resources, capacities and authority may not be sufficient to enable certain adaptation options to be realized.

16.7.1.1. Opportunities for Implementing Adaptation

There is evidence of public policy activity at the national and regional level in many parts of the world (see, for example, Chapter 15 for a discussion of National Action Plans for Adaptation (NAPAs)). Assessments of climate adaptation policies in Europe (Biesbroek *et al*., 2010; Massey and Bergsma, 2008) and North America (Luers and Moser, 2006; Moser and Luers, 2008; Moser *et al*., 2008) show that governments at different levels have recognized the importance of climate change and their potential role in adaptation. Accordingly, more structured policy frameworks and mechanisms to build capacity and advance adaptation are evident (16.8). Nevertheless, clear strategies for the implementation of substantive policies to reduce vulnerability to climate change and evaluate success are still lacking (Berrang-Ford *et al*., 2011; Ford *et al*., 2011; Preston *et al*., 2011a; Brouwer *et al*., 2013).

One of the primary strategies for enabling adaptation by private actors and securing public goods, such as ecosystem services, is through 'mainstreaming' climate vulnerability and adaptation into public policies (Urwin and Jordan,

2008; Dovers and Hezri, 2010). Mainstreaming involves a series of normative, organizational and procedural strategies that attempt to raise the profile of climate change at different stages of the policy cycle and to embed consideration of climate change impacts and adaptation in decision-making and policy evaluation (Mickwitz *et al.*, 2009; Rayner and Jordan, 2010). Mainstreaming is not without its challenges. For instance, there will be a question about whether 'principled priority' (Lafferty and Hoyden, 2003) should be given to climate adaptation goals over other goals, such as economic development or environmental protection. There is also a question over the extent of the coordination between policy domains that may be necessary. While key sectoral policy makers may accept the necessity for adaptive actions to ensure delivery of policy objectives into the long-term and adjust policies accordingly, they may fail to coordinate with efforts of other sectors. The result may be piecemeal approaches (Ellison, 2010) or incoherent, conflicting strategies (Pittock, 2011). For example, enhancing infrastructure for irrigation in arid areas to allow water-intensive agriculture to continue could hinder adaptation in other sectors, such as nature conservation.

A number of proposals have been made for public policy strategies that enable adaptation in the face of deep uncertainty. Hallegatte (2009b) describes five approaches to management decisions under conditions of uncertainty: "…*(i) selecting 'no-regret' strategies that yield benefits even in absence of climate change; (ii) favouring reversible and flexible options; (iii) buying 'safety margins' in new investments; (iv) promoting soft adaptation strategies, including (a) long-term (perspective); and (v) reducing decision time horizons*." By applying these principles, policymakers can create the conditions for better adaptation decisions by public agencies and in the private sector. In a similar vein, Stafford Smith *et al*. (2011) propose decision-making strategies for public policymaking, matching these strategies to the nature of uncertainty being faced in a specific decision context. They argue for a precautionary approach, risk-hedging against alternative futures and 'robust decision making' (see Chapter 2), where appropriate. Moser and Leurs (2008) suggest a series of enabling conditions for adaptation. These include taking account of the full range of adaptation options available (including apparently unattractive ones); making resources available for chosen options (singly or in portfolios) to be implemented; getting the institutional setting right in terms of incentives and penalties; making human and social capital available; enabling risk-spreading; and providing information allowing for good public understanding of stresses, risks and trade-off. In summary, adaptation opportunities are an outcome of an emphasis on flexibility, consistency and predictability, transparency and accountability in decision-making (Maddocks, 2012).

16.7.1.2. Ancillary Benefits of Adaptation

Adaptation in response to climate change vulnerabilities can achieve important co-benefits. While adaptation activities have often been developed and implemented in an *ad hoc* fashion (Ahmed and Fajber, 2009), adaptation efforts increasingly capitalize on complementarities by mainstreaming adaptation into existing policies and management activities (16.7.2). Although existing options provide a foundation to normalize adaptation (Dovers, 2010), it is important that the assessment and selection of adaptation responses consider a range of stressors, and, the need for adaptive management given future uncertainty.

Co-benefits may arise in three main ways – through improved implementation of adaptation to current climate variability; through exploiting new opportunities that arise as a result of the provision of climate adaptation goods and services; and through more general impacts on sustainable development.

- *Stimulating adaptation to current climate variability*: While it is generally assumed that physical, ecological and social systems are well-adapted to current climatic conditions; this is frequently not the case (Smit, 1993; Heyd and Brooks, 2009; Dugmore *et al*., 2009). Changes in observed climate, as well as the attention to such change, may lead currently maladapted actors and organisations to make changes that bring net benefits.
- *Provision of climate adaptation goods and services*: Adaptation will generally require additional investment and effort. It therefore represents an economic opportunity for some producers of goods and services. For example, the market for snow machines will be influenced by growing concerns about snow cover in more marginal ski resorts (Scott *et al*., 2006). In Arizona's high elevation, low latitude ski resorts by 2050, temperatures will may exceed technical thresholds in the shoulder seasons meaning that in years when natural snowfalls are poor the ski season may be curtailed. Higher elevation regions will see new

opportunities as a result of snow resort shifts (Bark *et al*., 2010). Likewise, new and innovative railway track and drainage systems may develop a market for dealing with track buckling caused by higher summer temperatures (Bark *et al*., 2010). The Stern Review suggested that huge market opportunities exist for new infrastructure and buildings resilient to climate change in OECD countries, with a potential value of between £9.5bn and £94.8bn per year (Stern *et al*., 2006). New services related to climate prediction and insurance also may emerge. Rising damage caused by climate change could provide new markets for innovative insurance products. Insurance can play an important role managing risks associated with climate-related damages (Botzen *et al*., 2009; Botzen *et al*., 2010).

- *Advancement of sustainability*: Economic development policies and strategies related to management of water and governance of natural resources, the development of water, transportation, and communication infrastructure, and the promotion of credit and insurance services can promote economic development, increase adaptive capacity and reduce the impacts of climate change on the poor (Hertel and Rosch, 2010).

16.7.2. Approaches to Overcoming Constraints and Avoiding Limits

There is a growing body of knowledge, including tools and guidelines, on the implementation of climate change adaptation responses which is addressing information and knowledge constraints on adaptation. This information provides a very wide range of views on how constraints may be overcome and opportunities taken. One of the important early initiatives in this area was the 'Assessment of Impacts and Adaptation to Climate Change' project under the START Program, which prompted an increase in research and policy interest and engagement in implementation (Mataki *et al*., 2006). In general, the information remains largely fragmented, although there is a major international effort underway to extract value from this knowledge through several actions of the Nairobi Work Program of the UNFCCC.

Opportunities for advancing implementation are becoming increasingly available through policies, tools and guidelines that are emerging throughout the developed and developing world addressing national, sub-national and local urban scales. For example, there is growing recognition of the potential for using disaster response and recovery processes as a means of increasing resilience to future extreme events (Lavell *et al*., 2012), although such opportunities require awareness and procedures to allow them to be taken. Examples of national responses include the USA '*Instructions for Implementing Climate Change Adaptation Planning in Accordance with Executive Order 13514*' (CEQ, 2011) and South Africa's '*National Climate Change Response White Paper*' (Government of South Africa, 2011). Many similar initiatives have been launched at sub-national and local levels with some early lessons about overcoming constraints to implementation being learned. For example Pickets (2012) states that many opportunities exist to incorporate adaptation-related principles and objectives into 'Official Community Plans', referring to storm-water management, water supply management, infrastructure planning, ecosystem mapping, and flood risk mitigation. Pickets (2012) also reports that incorporating climate change adaptation into existing plans and policies (i.e. mainstreaming) is effective in prioritizing implementation. However, there is far less information to assess how the theoretical body of adaptation knowledge has been applied, and the outcomes that have resulted, International networks of local governments (*e.g.,* Local Governments for Sustainability, ICLEI) will provide an important source of potential information on the effectiveness of implementation, and how constraints are being overcome and opportunities taken.

At present, the study of limits to adaptation is immature, with very few published data and little robust information available. As stated by the Australian National Climate Change Adaptation Research Facility (Jenkins *et al*., 2011; McNamara *et al*., 2011), the study of adaptation concerns mainly what adaptation can achieve, and not what is unachievable. Because limits to adaptation may be determined by a mix of physical, economic, technological and socially-related factors, and because history suggests behavioral responses affect the outcome of exceeding or avoiding limits, there is an urgent need to identify the social context that increases the chance of avoiding limits to adaptation.

Frequently Asked Questions

FAQ 16.1: Are there limits to adaptation to climate change?

Climate variations in the past sometimes went beyond what communities and societies at the time were able to cope with. Climate change during this century is also very likely to go beyond the limits of some of those needing to adapt. The greater the magnitude of climate change, the greater the likelihood that adaptation will encounter these limits. Limits exist both in the natural world and in society; some limits are hard while other ones are soft. For example, the rate of sea-level rise determines whether or not healthy coastal ecosystems can adapt by growing landwards or upwards. Beyond a certain rate these ecosystems will not be able to keep pace; this is a hard limit. Soft limits are reached when adaptation can no longer avoid a situation in which people's needs and values are compromised due to adverse effects of climate change. The location of both hard and soft limits is determined both by the degree and rate of climate change (and is therefore a function of mitigation pathways) and by the degree and rate of non-climatic stresses affecting the resilience or adaptive capacity of natural and human systems. Little empirical information is available on the functional relationships between climate change, non-climatic stresses and the emergence of limits to adaptation, offering scant support to the idea that the 2°C global goal represents a limit.

FAQ 16.2: To what extent can sustainable economic development, innovation, and technological change reduce adaptation constraints and contribute to the avoidance of limits?

There is a strong perception that economic development has enabled actors to deploy greater financial resources, technology, and human capital in managing risks due to climate change. However, the role of externalities of such development such as habitat degradation and, resource depletion, and climate change in increasing these risks has not been well quantified. A portfolio of local, national, and international strategies will be needed to facilitate sustainable development that expands the range of climate to which socio-ecological systems can adapt.

FAQ 16.3: Are limits to adaptation predictable?

Knowledge about limits to adaptation could inform the level and timing of mitigation and might justify early mitigation action. There is high confidence that limits to adaptation exist, but detailed understanding of the level at which climate change exceeds a limit is available only for a small number of natural systems and crop species. Research on adaptation by people often considers, explicitly or implicitly, technological change, financial resource availability, and other factors determining adaptive capacity, as well as physical and ecological impacts of climate change. However, any assessment of limits to adaptation in human systems is preliminary and of little use in decision-making, because of uncertainty about the existence and level of adaptation limits, and the soft nature of these limits. Furthermore, non-climatic trends and conditions, including uncertainty regarding actors' objectives and values and how they evolve over time, interact with climate change to further challenge the prediction of limits.

FAQ 16.4: What are the consequences of exceeding adaptation limits?

The exceedance of a socio-ecological system's limits to adaptation unavoidably results in a transformational change. This transformation may be adaptive through changes in management objectives, policy instruments, institutions and attitudes that enhance sustainability. Alternatively, transformation may be destructive resulting in loss and damage. As multiple values and objectives are often attached to biophysical and socioeconomic systems, transformation may involve trade-offs whereby some values are preserved while others are lost. As such, the exceedance of adaptation limits may raise ethical questions regarding how trade-offs are managed among different actors and, particularly, public versus private goods.

Cross-Chapter Box

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based approaches to adaptation (also termed Ecosystem-based Adaptation, EBA) integrate the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe *et al.*, 2011; Munroe *et al.*, 2011). EBA is implemented through the sustainable management of natural resources, as well as conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate

variability and change (Colls *et al.*, 2009). The CBD COP 10 Decision X/33 on Climate Change and Biodiversity states further that effective EBA also "takes into account the multiple social, economic and cultural co-benefits for local communities".

The potential for EBA is increasingly being realized (e.g., Munroe *et al.*, 2011), offering opportunities that integrate with or even substitute for the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees, may adversely affect biodiversity, resulting in maladaptation due to damage to ecosystem regulating services (Campbell *et al.*, 2009, Munroe *et al.*, 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). Well-integrated EBA is also more cost effective and sustainable than non-integrated physical engineering approaches, and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. EBA also offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes.

EBA provides opportunities particularly in developing countries where economies depend more directly on the provision of ecosystem services (Vignola *et al.*, 2009), to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang *et al.*,). In these settings, ecosystem-based adaptation projects may be readily developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan *et al.*, 2012, Midgley *et al.*, 2012; Roberts *et al.*, 2012)

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Midgley *et al.*, 2012, Opperman *et al.*, 2009).
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands and deltas) to provide effective measure against storm-surges, saline intrusion and coastal erosion;
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding;
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques;
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

It is important to assess the appropriate and effective application of EBA as a developing concept through learning from work underway, and to build understanding of the social and physical conditions that may limit its effectiveness. Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang *et al*. (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.]

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Table 16-1: Constraints affecting the implementation of adaptation policies and measures.

Constraint	Examples
Knowledge and Information	• Uncertainty regarding future climate change (Hulme *et al*., 2009; Dessai *et al*., 2009; Wilby and Dessai, 2010) • Uncertainty regarding future socioeconomic states and associated uncertainties (Preston et al., 2011b) • Lack of information regarding adaptation options and their costs and benefits (Prato, 2008; de Bruin *et al*., 2009b; Patt *et al*., 2010) • Incomplete information regarding the various constraints on, or limits to, the effectiveness of adaptation options (Mitchell *et al*., 2006; Moser, 2009; Smith *et al*., 2008b; Moser and Ekstrom, 2010; Conway and Schipper, 2011) • Lack of consensus regarding the appropriate balance between traditional and formal scientific knowledge (Box 16-2)
Natural Resources	• Growing consumption of water by humans is threatening the sustainable yield of surface and groundwater systems in a number of global regions (Bates *et al*., 2008; Shah, 2009; Goulden et al., 2009; Gober and Kirkwood, 2010; MacDonald, 2010; Taylor et al., 2012) • Non-climatic stresses to ecological systems can reduce their resilience to climate change (Malhi *et al*., 2009a,b; Diaz and Rosenberg, 2008; Kapos and Miles, 2008; Afreen *et al*., 2011). • Degradation of coastal wetlands and coral reef systems may reduce their capacity to buffer coastal systems from the effects of tropical cyclones (Das and Vincent, 2009; Tobey *et al*., 2010; Gedan *et al*., 2011; Keryn *et al*., 2011; CC-EA). • Soil degradation and desertification reduce crop yields and the resilience of agricultural and pastoral livelihoods to climate stress (Iglesias *et al*., 2011; Lal, 2011).
Financial Resources	• Financial capital is a key determinant of vulnerability and adaptive capacity of farmers and land managers to climate variability and change (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa *et al*., 2009, 2011; Jantarasami *et al*., 2010). • The costs of investigating and responding to climate change are perceived to be significant constraints on adaptation for local governments (Gardner *et al*., 2010; Smith *et al*., 2008b; Measham *et al*., 2011) • The reallocation of overseas development assistance to adaptation may divert resources away from programs and projects targeting development goals (Ayers and Huq, 2009) • Availability of adaptation finance through the clean development mechanism is declining (AFB, 2012)
Technology and Infrastructure	• Climate impacts to existing infrastructure and the needs for new infrastructure dominate aggregate estimates of adaptation costs (see Chapter 17, World Bank, 2006; Nicholls, 2007; UNDP, 2007; UNFCCC, 2007; Parry *et al*., 2009). • Inadequate technology and infrastructure is a key determining factor of the 'adaptation deficit' of particular regions and sectors (Burton 2004, 2005; Burton and May 2004). • Technological innovation and deployment is important for facilitating adaptation in agriculture (Hillie and Hlophe, 2007; Howden et al., 2007; Bates *et al*., 2008; Fleischer *et al*., 2011). • Technology is important for managing the risks of climate change and sea-level rise to coastal communities (Nicholls, 2007; van Koningsveld *et al*., 2008). • Awareness, uptake and use of technology is determined by multiple factors including education, financial resources, and cultural attitudes (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa *et al*., 2009, 2011).
Human Resources	• Lack of leadership on adaptation is a key constraint to adaptation planning and implementation (Gupta *et al*., 2010; Tompkins *et al*., 2010; Termeer *et al*., 2012; van der Berg *et al*., 2010) • Human resources influence the capacity of public health systems to manage climate risk (Ebi and Semenza, 2008) • Multiple stressors to mental health can impair cognition and effective decision-making around adaptation (Dias-Ferreira *et al*., 2009; Spears, 2011)

Table 16-2: Examples of potential trade-offs among adaptation objectives.

Sector	Strategy	Adaptation Objective	Real or Perceived Externality	References
Agriculture	Biotechnology and genetically modified crops	Enhance drought and pest resistance; enhance yields	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments	Howden *et al*. (2007); Nisbet and Scheufele (2009); Fedoroff *et al*. (2010)
	Subsidized drought assistance; crop insurance	Provide financial safety net for farmers to ensure continuation of farming enterprises	Creates moral hazard and inequality if not appropriately administered	Productivity Commission (2009); Pray *et al*. (2011); Trærup (2011); O'Hara (2012); Vermeulen *et al*. (2012)
	Increased use of chemical fertilizer and pesticides	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased discharge of nutrients and chemical pollution to the environment; increased emissions of greenhouse gases; increased human exposure to pollutants	Gregory *et al*. (2005); Howden *et al*. (2007); Boxall *et al*. (2009)
Biodiversity	Migration corridors; expansion of conservation areas	Enable natural adaptation and migration to changing climatic conditions	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges	Hodgson *et al*. (2009); West *et al*. (2009); Krosby *et al*. (2010); Levin and Petersen (2011)
	Anticipatory endangerment listings	Enhance regulatory protections for species potentially at-risk due to climate change	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to economic development	Clark *et al*. (2008); Ragen *et al*. (2008); Bernanzzani *et al*. (2012)
	Assisted migration	Facilitate conservation of valued species	Potential for externalities for ecological and human systems due to species relocation	Lovejoy (2005, 2006); McLachlan *et al*. (2007); Dunlop and Brown (2008)
Coasts	Sea walls	Protect assets from inundation and/or erosion	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands	Nicholls (2007); Hayward (2008); Hallegatte (2009); Zhu *et al*., (2010)
	Managed retreat	Allow natural coastal and ecological processes; reduce long-term risk to property and assets	Undermines private property rights; significant governance challenges associated with implementation	Rupp-Armstrong and Nicholls (2007); Hayward (2008); Abel *et al*. (2011); Titus (2011)
	Migration out of low-lying areas	Preserve public health and safety; minimize property damage and risk of stranded assets	Loss of sense of place and cultural identify; erosion of kinship and familial ties; impacts to receiving communities	Hess *et al*. (2008); Helberg *et al*. (2009); McNamara and Gibson (2009); Adger *et al*. (2011)
Water resources management	Desalination	Increase water resource reliability and drought resilience	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation	Adger and Barnett (2009); Barnett and O'Neill (2010); Becker *et al*. (2010); Rygaard *et al*. (2011); Tal *et al*. (2011)
	Water trading	Maximize efficiency of water management and use; increases flexibility	Undermines public good/social aspects of water	Alston and Mason (2008); Bourgeon *et al*. (2008); Donohew (2008); Mooney and Tan (2012); Tan *et al*. (2012)
	Water recycling/reuse	Enhance efficiency of available water resources	Perceived risk to public health and safety	Hartley, 2006; Dolcinar *et al*., 2011

Table 16-3: Sectoral synthesis.

Sector	***Framing***	***Adaptation Objective***	***Rate of change***	***Opportunities***	***Constraint***	***Limits***	***Synthesis***
Freshwater resources [Chapter 3]	Major emphasis needs to be given to governance reform to build the capacity for climate change adaptation and design and implementation of resilient system. Adaptation involves measures to alter hydrological characteristics to suit human demands, and measures to alter demands to fit conditions of water availability [3.6.6]. Therefore, there is a concerted effort away from "predict and provide" to enhancement of adaptive water management techniques including Integrated Water Resource Management (IWRM) joined with Strategic Environmental Assessment (SEA)[3.6.1, 3.6.3].	Avoid adverse impacts (e.g. floods and droughts) to the economy (e.g. economic losses) and the society (e.g. affected population) through strategic water resource management by incorporating adaptation options in planning and implementation of best practices, and enhance adaptive water management techniques [3.6.1]. Move from "predict and provide" approach towards adaptive water management and the adoption of 'resilient' approaches [3.6.3], and investments in risk-based actions [3.6.4].	Intense precipitation events will become more frequently and droughts will be more severe [3.3.1.4] and rates of mass loss of glaciers is likely to increase [3.4.4.2]	Climate change is frequently cited as a key motivation for the adoption of adaptive water management [3.6.3 and Table 3.3] provides a list of Adaptation Options including improve information, improve water management practices, improve the design and operations of water services, reduce water demand and waste, increase water supply and reliability, prevent pollution, reduce impacts of natural disasters, IWRM. Opportunities for improvements include "no regret" actions - those that generate net social and/or economic benefits regardless of whether climatic change occurs [3.6.3 and FAQ 3.6].	Specific constraints include: Structural: Long-lived infrastructure and the prevailing of large infrastructure as prevailing design [3.6.1]. Governance/Institutional: Sectoral fragmentation, lack of reform to manage uncertainty and surprise [3.6.1]. Institutional structures that limit stakeholder engagement and the uncertainty in how climate change may affect the water management system [3.6.3]. Economic (Human and financial capital) constraints include high economic costs and the failure to estimate actual costs [3.6.2], the high cost of implementation. Lack of financial resources. Technological, Information and Science: Uncertainty in the projected future changes makes it impossible for practical purposes to construct quantitative probability distributions of climate change impacts [3.6.5]. Lack of guidance on how the adaptive water management approach works when addressing climate change over the next few decades [3.6.3]. Access constraints including technology, information, capacity, institutions and capital, particularly in the developing countries [Table 3.4]. Lack of technical capacity, financial resources, awareness, and communication in developing countries [3.6.4]. Social/Psychological/Cultural: *[Need specifics/update from SOD]* Other: *[Need specifics/update from SOD]*	Nothing mentioned explicitly; the subsection on limits to adaptation (3.6.4) discusses constraints.	Changes in precipitation patterns and reduction in glacier volume may lead to reductions in river flows and falling groundwater tables, and cause saline intrusion in rivers and groundwater in coastal areas and that reduction in local water sources will lead to increased demand on regional water supplies [3.5.1] and significant declines in freshwater species globally [3.5.5]. Costs will be ca. USD 531 billion through 2030 to provide a sufficient water supply, given present and future projected water demands and supplies in more than 200 countries, the adaptation (Kirshen 2007, [3.6.2].

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
Terrestrial and inland water systems [Chapter 4]	There is a potential for autonomous adaptation by ecosystems and species including the capacity to migrate and human assisted adaptation including adaptive management, assisted, migration and restoration [4.4.1, 4.4.2]	Increasing the capacity of target organisms, ecosystem or Social-Ecological System to survive and function at an acceptable level, in the presence of climate change [4.4.2].	Capacity of autonomous adaptation for ecosystem and their constituent organisms is insufficient to cope with the rate and magnitude of change under moderate and high climate change scenarios for this century [4.4.1-4.4.1.2, 4.4.3]	Opportunities to facilitate adaptation stems from the implementation of planned or "human-assisted" adaptation including reduction of non-climatic stresses [4.4.2.1], strategic number, location and connectedness of protected areas [4.4.2.2], landscape and watershed management [4.4.2.3], assisted migration and restoration [4.4.2.4] and ex-situ conservation [4.4.2.5]	*Specific constraints include*: Access: *[Need specifics/update from SOD]* Structural: Autonomous adaptation constrained by physical or topographic barriers (*e.g.,* valleys, mountain ranges and water bodies), human-created (fences, roads, croplands or settled areas), increasing habitat fragmentation of ecosystem. [4.4.3]; Lack of suitable habitat and dispersal pathways for species, inability to reduce or remove of other stressors, societal resistance Governance: Social and institutional factors including poor ecological understanding are constraints for successful adaptive management [4.4.2]. Economic (Human and financial capital): *[Need specifics/update from SOD]* Information and Science: Inadequate predictive theory for range shifts and extinction risk, combined with climate scenario uncertainty constrain conservation planning.	A clear consensus that climate change will result in shifts in species ranges, that constraints on migration for many species, in the context of highly fragmented habitats and other pressures, will greatly increase extinction risk over the coming century. [4.3.3] Phenotypic or genotypic evolution inadequate to ensure population persistence causing local to global extinction [4.4.1.2]	The most recent synthesis of range shifts indicates that terrestrial species have moved poleward which corresponds to predicted range shifts due to warming (Chen *et al*., 2011) and that range shifts for terrestrial species will accelerate over the coming century. [4.3.2.5] Significant proportion of coral reef species and terrestrial species at risk of extinction, as temperature change increases above 2 to 3 degrees. The cost of adaptation to ensure persistence in the wild increases due to land availability and translocation costs.
Coastal systems and low-lying areas [Chapter 5]	Adaptation occurs in the context of existing governance and social-ecological systems, regardless of types of adaptation (i.e. proactive and planned or reactive and ad hoc) the approach should be integrative and implemented through adaptive management [5.6.1]	Minimize risks and impacts from coastal hazards to ensure public safety and welfare; economic development and use of coastal resources; protection of coastal environmental resources, natural assets and ecosystems (5.6.1)	The coastal ecosystems are affected by higher sea level, increasing temperature, changes in precipitation, increased extreme events and reduction in ocean pH from climate change and rapid urbanization in coastal areas and growth of megacities with consequences on	Implementation of the many approaches on integration for better social, ecological, and economic outcomes including Integrated Coastal Management, Community-Based CoAdaptation, Ecosystem-Based Adaptation (EbA), and Disaster Risk Reduction and Management. [5.9.1]	Different constraints typically do not act in isolation but interact [5.9.4] Constraints are many and fall into many categories including the technological feasibility, resources, institutional (existing laws, regulations, procedural requirements or ineffective governance), social and psychosocial (place attachment, social support, social norms, identity), cultural-cognitive (beliefs, worldviews, values, awareness, education) and economic (livelihood, job mobility, investment), lack of awareness, knowledge or location-specific information, social justice concerns, or negative interactions between different policy goals. [Table	Managed retreat from coastal system as adaptation option implemented in response to a soft limit to adaptation FAQ 5.6. Limits to adaptation will be experienced by migrating species and habitat types as sea level rise	The most important effects of climate change on the coastal cities include the effects of sea-level rise, effects of extreme events on built infrastructure (such as wind storms, storm surges, floods, heat extremes and droughts), effects on health, food and water-borne disease, effects on energy use, and

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
			the coastal resources. [5.1]. Global mean sea level (MSL) has been rising since 1900 at a rate of 1.7 mm yr^{-1} and 3.2 mm yr^{-1} since 1993 (AR5, Chap 13).		5-7, 5.9.4] *Specific constraints include*: Access: *[Need specifics/update from SOD]* Structural: Continued development in high risk areas [5.6.1]. Governance/Institutional: The prevalence of mal-adaptation due to interactions across policy domains [5.6.4]. Economic (Human and financial capital): economic constraints at the individual level, institutional and government levels that prevent implementation [5.6.4]. Technological, Information and Science: *[Need specifics/update from SOD]* Social/Psychological/Cultural: *[Need specifics/update from SOD]* Other: *[Need specifics/update from SOD]*	meets human settlements [5.3.1] including coastal marshes [5.6.4]. The decline of seawater pH decreases the rate of calcification of most corals, presenting a limit to coral reef adaptation [5.3.1.6]. Physical limits to unassisted adaptation of coastal marshes as sea levels rise past A1B scenario (5.6.4)	effects on water availability and resources (Hunt and Watkiss, 2010) [5.4.2.1]. The total assets exposed in 2005 across all cities are estimated to be US$3 trillion, which would increase to US$35 trillion by 2070s (Nicholls *et al.*, 2008; Hanson et al., 2011) [5.4.2.1]
Ocean systems [Chapter 6]	Ecosystem resilience and marine ecosystem based adaptation [6.4] There is a potential for autonomous adaptation for species and population including through genotypic variation and migration [6.2.2.2]	Resilience of fisheries. *[Update for SOD as majority of adaptation discussion focused on species adaptation to increasing temperatures and changes in acidity]*	Over the last 43 years average warming has occurred by >0.1 °C/decade in the upper 75 m with increase of X% through 2070 [6.1.1.1]. The changes in ocean temperature and acidification will drive changes in nutrients con, salinity, underwater light regime net primary	Opportunities for adaptation of human populations dependent on ocean resources, particularly in developing countries, are limited [6.4.1.1.2]	Constraints are related to ocean temperature, acidification, etc that limit functions of ocean and supply of primary elements to living organism thus preventing autonomous adaptation [6.4]. *Specific constraints include:* Access: *[Need specifics/update from SOD]* Structural: *[Need specifics/update from SOD]* Governance/Institutional: *[Need specifics/update from SOD]* Economic (Human and financial capital): *[Need specifics/update from*	Marine species that already live close to their upper thermal and pH limits will be most sensitive to climate change. There have been reports on climate-induced changes in species abundances but not on climate-induced extinctions in the oceans [6.5.2].	Fisheries and ecosystem management in the future might have to deal not only with the traditional sustainability goals, but to increase the ecosystems resilience to climate variability and change [6.4.2.5] Adaptation and management of risks will build on successful detection and attribution. Ecosystem-based

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
			production and food availability [6.1, 6.2],		*SOD]* Technological, Information and Science: *[Need specifics from SOD]* Knowledge gaps on whether and to what extent species can undergo adaptation to progressive ocean acidification over generations [6.2]. Social/Psychological/Cultural Other: *[Need specifics from SOD]*	Evidence regarding limits to adaptation are scarce for ocean systems however one study finds a limit in which aragonite undersaturation is projected to occur by the year 2030 leading to a decrease rates of calcification and increasing ocean acidification [McNeil and Matear 2008]	management (EBM) with a focus on climate change impacts will need adopted to manage the multitude of anthropogenic pressures on marine ecosystems, [6.4.3]
Food production and food systems [Chapter 7]	Adaptation through reductions in risk and vulnerability by adjusting practices, processes and capital in response to current climate or threat of climate change [7.5.1],	Reduce and vulnerability by adjusting practices, processes and capital [7.5.1.1] to address the eight elements of the food security outcomes including income, employment, wealth, social capital, political capital, human capital, ecosystem stock and flows, ecosystem services and access to natural capital (Figure 7-1).	Crop yields are likely to fall by at least X% by the year 20XX [7.4.4.] with the highest rates of food insecurity are in Sub-Saharan Africa *[Need specifics/update from SOD]*	Opportunities include taking advantage of the increase in the growing season, the range expansion, and yields [7.5].	Constraints include inadequate information on climate, climate impacts, risks and benefits of options, lack of adaptive capacity, technical options, inadequate extension, institutional inertia, financial resources, infrastructure, functioning markets and insurance systems [7.5.1] *Specific constraints include:* Access: *[Need specifics/update from SOD]* Structural: Lack of infrastructure. Governance/Institutional: Institutional inertia and lack of adaptive capacity [7.5.1.2.1], lack functioning markets and insurance systems. Economic (Human and financial capital): Lack of financial resources, Inadequacy of required substantial investment to develop new varieties of crops or breeds of livestock [7.5.1.2.1] Technological, Information and	Physiological limits to performance and crop yields requirement to sustain critical backward and forward link infrastructure. [7.5.1]	Adaptation of food systems shows a wide range in effectiveness. With an increase in effective with adaptations aimed at temperature increases which leads to lower reductions in yields than in its absence with more effective adaption at higher latitudes [Executive Summary] However, most reduction in risk are incremental, not transformative, and do not take into account the competing stressors of water availability and increased demand for food

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
					Science: Inadequate information on climate, climate impacts, risks and benefits of option. Lack of technical options. [7.5.1.2.1]. Social/Psychological/Cultural: Other: *[Need specifics/update from SOD]*		[7.5] Many of the elements in the human food system will be adversely affected by projected climate change from about the mid-21st century onwards. Adaptation options have potential to reduce 20 percent yield reduction [ES]. Ongoing increases in potential yield across the globe due to crop improvements may act to mitigate negative impacts (7.4.1)
Urban areas [Chapter 8]	Building resilience of urban infrastructure and social system by integrated planning, investment and addressing structural drivers of social and urban vulnerability [8.3.2.1]	Integrate/mainstream climate change adaptation in urban areas through government led city planning and implementation and disaster risk reduction [8.3.2], coordination of investment from individuals, household and firms, and other levels of government [Executive Summary].	Great diversity exists among the world's urban areas with rates of change as informed by the scale and nature of the climate-related risks. *[Need specifics/update from SOD]*	Opportunities exist in taking advantage of 30 years of experience in municipal disaster risk reduction and in building on the relation between adaptation to climate change and development [8.3.2.2], including implementation of ecosystem-based adaptation to support a range of policy goals including food security, water purification, waste water treatment and flood risk reduction as well as mitigation [8.3.3.7, Box 8.1]]	Constraints include resource limitations, limited adaptive capacity with limited resources, weak institutions, poor/inadequate infrastructure and poor governance in global south [8.5.1] *Specific constraints include:* Structural/capacity: Lack of technical expertise, Lack of capacity of multi-levels of government to implement coordinated plans and responses [Executive Summary] Governance/Institutional: Municipal government priorities driven by short term priorities and nearer term concerns about economic growth and competitiveness [8.4]. Ill-designed institutional mechanisms (compartmentalization and fragmentation) at local level [8.4]. Lack of mandate and clarity at different levels, inadequate policy attention and recognition by national	Coastal system that are inundated as sea level rises and river systems that flood create a soft limit to adaptation [8.4.1.2] unless strategic and managed retreat is developed in advance.	Adaptation in a 4 degree world will have to be a "more substantial, continuous and transformative process" than for a 2 degree world, and will have to contend with the possibility of thresholds, that once crossed, will lead to abrupt, non-linear and unpredictable global environmental change. This will stretch the adaptive capacity not only of existing urban systems, but of the whole global system [8.5].

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
					government [8.4]. Disaster risk reduction is still not integrated into development plans and not drawing in all relevant departments and divisions of local government. Implementation of hard engineering solutions and effectiveness are constrained by technological, financial, institutional and skill [8.3]. Lack of coordinating poverty reduction with climate change responses and making adaptation plans locally relevant [8.5] Economic (Human and financial capital): Lack f financial resources for implementation [8.4] Technological, Information and Science: Uncertainty as to what climate change will bring (and when) in each locality [Executive Summary]. Limited technical expertise. Poorly developed Monitoring, Reporting and Feedback systems [8.5]. Substantial knowledge gaps need to be addressed to determine where the limits or thresholds lay, limits or thresholds to adaptation of various ecosystems. Knowledge about limits within existing systems will be vital in developing appropriate transformative planning responses to future climate challenges [8.3; 8.5] Social/Psychological/Cultural: *[Need specifics/update from SOD]* Other: *[Need specifics/update from SOD]*		
Rural Areas [Chapter 9]	Adaptation, and building capacity to adapt, is a dynamic process and should be linked to other development initiatives aiming for poverty reduction or improvement of rural	Development of resilient agriculture, economic and institutional development, improvements in health, education and infrastructure, growing	Prospects for adaptation depend on the magnitude and rate of climate change, adaptation strategies being inseparable from increasingly strong and complex	Opportunities to benefit rural communities come from expanding the use of seasonal forecast information for coordinating input and credit supply, food crisis	[*To be completed post-SOD]*	There are soft limits to the role of social capital in resilience which context specific and time bound [9.4.1].	Climate change in rural areas in developing countries will take place in the context of many important economic, social and land-use trends. In different regions,

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
	areas [9.4.1]	interconnectedness and technology transfers to help rural societies to develop their human and social capital and link adaptation to other development initiatives aiming for poverty reduction or improvement of rural areas.	global linkages [9.2].	management, trade and agricultural insurance [9.4.4]		Poverty, hunger, malnutrition are already significant challenges being exacerbated by climate variability in rural settings (mainly sub-Saharan Africa), attribution difficult because of the impacts of related and unrelated co-stressors, water supply, food production and agricultural income are seeing increasing residual damages, indicating the approach of limits in many regions [9.4.1].	rural populations have peaked or will peak in the next few decades [9.3.1]. Conservation agriculture and water management for agriculture is critical in rural areas under climate change and adjustment measures relating to there farming practices. Adaptation in marine ecosystems is also of relevance to rural areas. Need to discriminate between developing and developed country rural areas, with the latter at far higher risk of imminent limits, and heavily constrained by a number of factors.
Key economic sectors and services [Chapter 10]	To reduce the cost of adaptation.	*[To be completed post-SOD]*	*[To be completed post-SOD]*	*[To be completed post-SOD]*	*[To be completed post-SOD]*	*[To be completed post-SOD]*	*[To be completed post-SOD]*
Human health [Chapter11]	Climate change acts as a multiplier of risk – in most instances, changes in temperature; rainfall and extreme events compound health problems that are already present. [11.6.1]	Reducing background rates of disease and injury, improvements in public health and health care including access to heath care services for improvement of population resilience and minimizing poor health outcomes	There is a dearth of scientific evidence of the relationship between weather/climate and health in low- and middle-income countries [Box 11-2]	Cross-sectoral adaptation opportunities exists (transportation, building, landuse, forestry and agriculture (Younger et al., 2008). Reduction in disaster mortality through effective	Uncertainties of future climate and socioeconomic conditions, financial, technologic, institutional, social capital and individual cognitive limits, different knowledge and conceptual understanding by different actors/stakeholders, governance arrangements and the way institutions works (Huang, C, et al., 2010; Carmichael and Lambert, 2011) *Specific constraints include:*	Climate and/or health conditions that limit the body's ability to respond to stressful events [11.3.1.2].	Health is both a condition for, and a consequence of, development, and there is a similar inter-dependence between a country's social and economic progress and its ability to protect its population against adverse effects of

Sector	*Framing*	*Adaptation Objective*	*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
		resulting from climate change [11.6.1]		collaborations between government, local communities and non-governmental organizations (Khan 2008). Carbon abatement is an opportunity to achieve both climate mitigation and health benefits (UNEP, 2012).	Structural: *[To be completed post-SOD]* Governance/Institutional: *[To be completed post-SOD]* Economic (Human and financial capital): *[To be completed post-SOD]* Technological, Information and Science: Social/Psychological/Cultural: *[To be completed post-SOD]* Other: *[To be completed post-SOD]*		stressors such as climate change [11.1.1]
Human Security (Chapter 12)	Human security in the inverse of social vulnerability in that it implies the protection of people from severe shocks arising from changes in social or environmental conditions [Executive Summary].	Enhance human security through social and environmental policies and programs that ensure social protection and expand people's freedoms and opportunities necessary for survival, sustainable livelihoods, and dignity [12.1.2].	[*To be completed post-SOD]*	Opportunities include migration to enhance human security to climate change impacts [ES].	Lack of flexibility in where and when to relocate, access to resources, changes in the resource base, resource management, encroachment and institutional constraints, *Specific constraints include:* Structural: *[To be completed post-SOD]* Governance/Institutional: [*To be completed post-SOD]* Economic (Human and financial capital): [*To be completed post-SOD]* Technological, Information and Science: Neglecting local and traditional knowledge in policy and research [12.3.2] Social/Psychological/Cultural: Poverty widens disparities and lack of proper entitlements or rights for managing and using resources [12.3.4] Other: [*To be completed post-SOD]*	No hard limits identified but at very high rates of projected warming, all of the aspects of human security likely to be adversely effects creating soft limits that may be difficult to overcome [12.7]	Climate change seems likely to be an increasingly important driver of human insecurity in the future [12.7]
Synthesis	[*To be completed post-SOD]*	*[To be completed post-SOD]*	[*To be completed post-SOD]*	[*[To be completed post-SOD]*	[*To be completed post-SOD]*	[*To be completed post-SOD]*	[*To be completed post-SOD]*

Table 16-4: Regional synthesis.

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
Africa [Chapter 22] [22.3.4: adaptation section is forthcoming]	Mainstreaming adaptation to climate change into national development policies. Sub-regional organizations integrate climate change in their policies and economic management.	Strengthening adaptive capacity of rural and urban contexts by mainstreaming climate change into national development policies as well as sub-regional organizations integrate climate change in their policies and economic management.	*[To be completed post-SOD]*	Opportunities for adaptation include linking adaptation and development, and for low-regrets adaptation strategies that produce developmental co-benefits [22.4], including integrated programmes on desertification, water management and irrigation, promoting sustainable agricultural practices, developing alternative sources of energy [22.4.1] and implementing ecosystem-based adaptation [22.6.5] In addition, reducing health burdens through improving public health surveillance and monitoring, access to safe water and improved sanitation, hygiene education, and waste management strategies; and providing better access to health care and health insurance [22.3.3.2.3]	The constraints to adaptation in Africa interact in multiple and complex ways across scales influencing how local people both decide or are enabled to respond or not to changes in their environment [22.4.4]. *Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Corruption, inadequate extension services and top-down decision making. Institutional weakness, Over-emphasis of mitigation discourse, emphasis of short-term outcomes with a disaster/risk orientation. Economic (Human and financial capital): Lack of resources [22.4.4]. Technological, Information and Science: Lack of capacity, data and integrated analysis related to climate change. Lack of knowledge regarding what influences decision making [22.4.4]. Social/Psychological/Cultural: Cognitive, behavioral and cultural constraints exist regarding the need to adapt and the willingness to accept change [22.4.4]. Other: *[Need specifics/update from SOD]*	Neither autonomous nor planned adaptation to climate change is necessarily materialising neither in the ways expected nor at the pace desired, and that simply providing the right technology and sufficient funding to carry out local level programmes is not a guarantee for change on the ground (Ludi et al. 2012) [22.4].	A wide range of adaptation options, approaches and decision tools are being tested and implemented across Africa but additional efforts at scale are needed to address the complex identified vulnerabilities and needs [Executive Summary], including disaster risk reduction, early warning systems and disaster preparedness; social protection and index-based weather insurance; technological approaches and climate-resilient infrastructure; sustainable land management and ecosystem restoration; and livelihood diversification [Executive Summary], .

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
Europe [Chapter 23]	Integration of climate change into national, local and sectoral development plan and strategies [23.7] aiming at improving competitiveness, the environment, and the quality of life in rural areas [23.7.5].	Focus on cross-sectoral decision making for adaptation with respect to four main categories of impacts: (1) production systems and physical infrastructure; (2) agriculture, fisheries, forestry and bioenergy production; (3) health and social welfare and; (4) protection of environmental quality and biological conservation [23.1.1].	*[To be completed post-SOD]*	Individual and cross sector opportunities are highlighted in each of the four main categories (1) production systems and physical infrastructure; (2) agriculture, fisheries, forestry and bioenergy production; (3) health and social welfare and; 4) protection of environmental quality and biological With a focus on recreation and tourism, insurance and banking, food (fiber, livestock, fish) production, water resources, forestry, disaster risk reduction (drought, flood), infrastructure, water quantity and quality, human health, social and cultural. *[Need specifics/update from SOD]*	*Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Lack of institutional frameworks is a major constraint to adaptation governance [23.10.1] and cross-sector adaptation plans. A lack cross-sector impact and adaptation linkages as an important weakness in the city plans [23.7]. Economic (Human and financial capital): *[Need specifics/update from SOD]* Technological, Information and Science: *[Need specifics/update from SOD]* Social/Psychological/Cultural: *[Need specifics/update from SOD]* Other: Irrigation for agriculture will be constrained by reduced runoff, demands from other sectors, and by economic costs [23.4.1, 23.4.3]. Lack of integrated coastal zone management or climate change adaptation for the Baltic Sea Region.	In agriculture, there are limits to increasing crop yields and production through genetic modification [23.10.1] In natural systems, phenological mismatches will limit both terrestrial and marine ecosystem functioning and ecosystem service production [23.6.4, 23.6.5]. Drought-pest dynamics in forest systems may be a limit to forest persistent and productivity through a state change [23.4.4]. There are soft limits to how far communities can adapt to rapid and large sea-level rise.	Climate change impacts and vulnerability assessments have given rise to an adaptation decision-making framework, at the local, regional, national and pan-European levels leading to the development of a series of national plans and strategies to address adaptation [23.7]. The next step is cross-sectoral decision-making and planning [23.7] in arenas such as Coastal Zone Management [23.7.1]. Integrated Water Resource Management (IWRM) [23,7,2]), land use planning [23.7.4] and rural development [27.7.5].
Asia [Chapter 24]	Adaptive management and mainstreaming climate change into development planning at all scales, levels and sectors [24.2.2].	Adaptive management and mainstreaming climate change into development planning at all scales, levels and sectors including cross-sectorial collaborations for the development of sustainable adaptive measures (24.4.6.5)	*[To be completed post-SOD]*	Opportunities are described in 6 categories (1) Freshwater resources: applying water saving technologies in irrigation, changing to drought tolerant crops, increasing water supply, and improving management [24.4.1.5]. (2) Terrestrial and inland waters: conserving the geophysical stage;	Constraints are identified broadly as being ecological, social and economic, technical and political. *Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Lack of co-ordination in the formulation of responses [24.2.2]. High degree of	Limits are identified as biophysical limits in ecosystems, including limits to dispersal and climate tolerance will lead to species extinctions [24.4.2.3].	Mainstreaming adaptation into government's sustainable development policy portrays a potential opportunity for good practice to build resilience and reduce vulnerability depending on effective, equitable and legitimate actions

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
				protecting climatic refugia, and increasing landscape connectivity [24.4.2.5]. (3) Coastal system and low lying areas: Hard coastal defenses and acquisition of landward buffer zones [24.4.3.5] (4) Food production systems: crop breeding [24.4.4]conservation farming, change to drought-tolerant crops, water conservation efficiency, crop shifting and diversification and strategic food reserves [Table 24.8] (5) Human settlements, industry and infrastructure: migration, land use change, green infrastructure, flood proofing [Table 24.9] (6) Human Health, Security, Livelihoods, and Poverty: Win-win solutions for public health from the interaction of adaptation and mitigation measures that involve urban environments and air pollution [24.7]. Climate resilient livelihoods can be fostered through the creation of a bundle of capitals (natural, physical, human, financial and social capital) and poverty eradication [Table 24-11]. Community based approaches to address poverty and livelihoods [24.4.6.5]. Technologies and policy options that provide both mitigation potential as well as sustained income generation potential	centralization of the management regime and the lack of vertical integration result low adaptive capacity (24.4.1.5). Lack if information sharing of best practices across countries. Insufficient mainstreaming of adaptation into the broader policy frameworks. Insufficient integration of transboundary policy recommendations into national climate change plans and policies [24.9.1]. Absence of involvement of upstream and downstream stakeholders. Lack of prioritization of employment generation and education as issues at the national level [24.5.4]. Weak governance mechanisms and breakdown of policy and regulatory structures [24.5.4]. Lack of disaster risk reduction [24.5.4]. Economic (Human and financial capital): Lack of financial resources for adaptation implementation [25.5.4]. Lack of higher education in adaptation [24.5.4]. Technological, Information and Science: Spatial and temporal uncertainties associated with forecasts of regional climate, limited national capacities in climate monitoring and forecasting [24.2.2]. Lack of awareness on the impacts of climate change to sustainable development [24.5.4]. Lack of research [24.4.4] Social/Psychological/Cultural: *[Need specifics/update from SOD]*		to overcome barriers and limits to adaptation (24.5.3) Success will depend on promoting good governance including responsible policy and decision making; empowering communities and other local stakeholders so that they participate actively in implementation of adaptation; and mainstreaming climate change into development planning at all scales, levels and sectors [24.2.2], [24.4.6.5].

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
					Other: Existence of biophysical constraints to climate change [35.5.4]		
Australasia [Chapter 25]	The opportunities for and effectiveness of adaptation depend heavily on institutional and governance arrangements that enable decision-makers to consider climate change information [25.5.1]	Maintenance, enhancing resilience and rational use of natural resources (e.g. water, ecosystem) through policy reforms for mainstreaming climate change that comprises an interdependent mix of strategies. Ameliorating some impacts and delivering multiple benefits by reducing other environmental stresses.	*[To be completed post-SOD]*	Adaptation opportunities are highlighted in each of the nine main categories (1) Freshwater Resources: securing water augmentation, sewage recycling and stormwater use, reduction of demand, and integrated planning with consideration of flood risk and stormwater and wastewater infrastructures (2) Terrestrial and Inland Freshwater Ecosystems; increasing resilience, targeted relocation of at-risk species into new habitats (3) Coastal and Ocean Ecosystems: managed retreat from eroding coasts (Box 25-2), removal of human barriers to migration, beach nourishment, translocation of species, management of environmental flows, habitat provision, and modification [25.6.3.3] (4) Production Forestry, species or provenance selection, silvicultural options [25.6.4.2.] (5) Agriculture: crop switching [25.6.5.2] (6) Mining: *[Need specifics/update from SOD]* (7) Energy Supply, Transmission, and Demand: limit increasing urban energy demand [Box 25.9] (8) Tourism: strengthening ecosystem resilience, preparation for extreme	*Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Unclear legislative frameworks, institutional fragmentation, and limited vertical and horizontal integration of different actors with unclear responsibilities, contradictory policies and development goals [25.5.2]. Absence of a consistent information base and binding guidelines that clarify governing principles [25.5.2]. Economic (Human and financial capital): Lack of financial resources particularly at the community level. Limited of social and institutional capital. Technological, Information and Science: Uncertainty about the scale and timing of projected impacts, limited financial and human resources [25.5.2]. Lack of robust frameworks to deal with the uncertainties and dynamic change characteristic of climate change; magnitude and rate of climate change, together with fragmentation of habitat limit migration options for species [25.6.2.3]. Social/Psychological/Cultural: Perception of climate change as a risk, social and cultural values that place attachment	Collapse of coral reef systems in north-eastern and western Australia, driven by increasing sea-surface temperatures and ocean acidification; the natural ability of reefs to adapt to the projected rates of change is very limited [Box 5-3, 25.6.3] Loss of montane ecosystems and some endemic species in Australia [25.6.2], Individual species and ecosystems that occupy climatically constrained ecological niches and/or occur in fragmented habitats or locations where adaptive movement is not possible; e.g. coral reef systems in northeastern and west Australia and ecosystems in the Australian alpine zone currently covered by seasonal snow (25.6.2, 25.6.3).	Adaptation is already occurring and adaptation planning is becoming embedded in planning processes. Capacity to adapt is generally high in many human systems but implementation of effective adaptation measures faces major constraints especially at local and community levels. Some impacts have potential to be severe but can be moderated or delayed significantly by combined global mitigation and a portfolio of available adaptation measures while some cannot be. Two key challenges for adaptation are apparent in the region: identifying when and where a departure from incremental to transformative adaptation measures is needed; and, where specific policies to facilitate proactive adaptation are needed to overcome barriers to mainstreamed and

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
				events [25.6.8.2] (9) Human Health: reshaping government policy, improving healthcare services, developing early warning systems, preparing health system/emergency system, improving maintenance programs for key services, seeking behavioral changes and community awareness to reduce exposure, developing emergency response plan {25.6.9.3] (10) Indigenous: *[Need specifics/update from SOD]*	and differing values on near- versus long-term and private versus public costs and benefits [Box 25-1]. Individual and collective social and cultural values. Other: *[Need specifics/update from SOD]*		autonomous adaptation [25.8.3]
North America [Chapter 26]	*None. [Need specifics/update from SOD]*	Adjusting water infrastructure and institutional mechanism, improving climate resilience and adaptation for ecosystem and biodiversity though changes approach to protected area planning, institutional shift for addressing wildfire	The region is very likely to face increasing warming and extreme high temperatures, higher sea levels, more intense precipitation and droughts, more intense storms, and reduced snowpack and higher sea levels. [26.1.1, 26.2.2, 26.4.1, 26.5]	Opportunities are highlighted in the following 12 sectors: (1) Water Resources and Management: drought management plans, reduced water consumption, system interconnections, improved coordination with other organizations, holistic management of storm water, flood waters, water supply, and wastewater management, incorporating climate change impacts into municipal bond ratings, diversification of supplies and source protection, land use management, better alignment of revenues with fixed and variable costs [23.6.1.2], increased efficiency in farm systems, cooperative crisis management among user, and adjustment water infrastructure [26.3.3], For flooding, updating elevation and land use datasets every 10 years, improved	*Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Decentralized response frameworks focusing reactive measures to cope with rather than preventing problems. Lack of decision-making on priority between extreme events vs. changes in long-term average conditions [Box 26.4]. Lack of coordination and institutional fragmentation of the different tiers of government. Lack of mainstreaming climate change issues into decision-making. Lack of willingness to address adaptation issues [Box 26.4]. Existing deficits in infrastructure. Lack of services (health, education) and institutional capacity [Box 26.4]. Cities with existing deficits in infrastructure (e.g., insufficient coverage, need of major upgrades and climate proofing), services (health, education), and institutional	None identified.	*[Need specifics/update from SOD]*

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
				hydrologic and hydraulic modeling, predicting extent of future floodplains as the climate changes and uncertainties decrease, eventually charging pre NFIP buildings full rates to decrease repetitive loss (2) Ecosystems and Biodiversity: changes in the approach to protected area planning, establishment and management, breeding programs for resistance to diseases and insect pests, alignment of adaptation and mitigation [26.4.3] (3) Wildfires: changes in institutional management, communications of risk [26.5.3] (4) Food Security: Change varieties, crop diversification, capital for on farm improvement in irrigation efficiency, climate tolerant crops, adapt to shifting fish distribution [26.6] (5) Rural Communities: investments into rural adaptive capacity (6) Indigenous Communities: traditional culture with contemporary forms of knowledge, education and economic development [26.7.1.2] (7) Tourism-based Communities: restoration [26.7.2.3] (8) Forest-based Communities: assisted migration, economic diversification, (9) Human Health: none. (10) Infrastructure: none. (11) Urban: create synergies and overcome conflicts with	capacity. Economic (Human and financial capital): High cost, energy and time required to construct, develop and maintain infrastructures and services. Insufficient financial and human resources to address the underlying processes of environmental deterioration [Box 26.4] Technological, Information and Science: Lack of a warning systems and emergency preparedness; lack of regional-to-local spatial scales climate scenarios [Box 26.4] Social/Psychological/Cultural: low social capital and limited economic resources [Box 26.4] Other: *[Need specifics/update from SOD]*		

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
				mitigation and other development goals, Infrastructural upgrades, early warning systems, developing shared-risk schemes for agriculture and livestock activities, and creating insurance schemes against disasters. They also include campaigns for raising public awareness, green infrastructure (12) Key Economic Sectors: introducing and expanding the role of insurance in developing markets [26.11.4.1]			
Central and South America [Chapter 27]	Reducing exposure and vulnerability and increasing resilience to the potential adverse impacts of climate extremes, even though risks cannot be fully eliminated [27.1.1.2]	*[Need specifics/update from SOD]*	The projected mean warming for CA and SA by the end of the century ranges from 2°C to 4°C for the SRES emissions scenario B2, and from 4°C to 8°C for scenario A2. Changes in rainfall and in extremes are more uncertain, especially in CA and tropical SA	Opportunities are highlighted in the following 8 sectors: (1) Freshwater Resources: increase in water supply through groundwater pumping and fog interception, increase infrastructure, reservoirs and irrigation infrastructure capacity, increase irrigation efficiency practices and change crop patterns [27.3.1.2] (2) Terrestrial and Inland Water Systems: Adoption of ecosystem-based adaptation practices [27.3.2.2], restoration (3) Coastal Systems and Low-Lying Areas: marine protected areas, coastal planning, retreat and resettlement [27.3.2.2] (4) Food Production Systems and Food Security: diversification and shifting of crop types, changes in fertilizer use, changes in growing season, genetic	Adaptation is heavily constrained by limited funding available from central governments and lack of institutional capacity to mainstream climate change into policy [27.3.1.2]. Other constraints include: *Specific constraints include:* Structural: Settlements highly vulnerable. Governance/Institutional: Lack of capacity-building and appropriate political, institutional and technological frameworks. Planning efforts focused at the national and regional level while most of the final adaptation implementation actions are local. Lack of structural reforms to provide good governance. Lack of decision-maker capacity-building, absence of a synergetic development-adaptation planning and funding. Economic (Human and	None identified.	Adaptive capacity of developing and emergent countries is low and coping with new situations may require new approaches such as a multilevel risk governance (Corfee-Morlot *et al*., 2011; Young and Lipton, 2006) associated with decentralization in decision making and responsibility [27.4].

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
				techniques, specific scientific knowledge and land-use planning, irrigation and use of rain water, shading, genetic modification of crops, (5) Human Settlements, Industry, and Infrastructure: mainstreaming flood management and warning systems, urban tree planting (7) Renewable Energy: bioenergy production, management of land use change, development of policies for financing and management of science and technology renewable energy [27.3.6.2] (8) Human Health: none.	financial capital): limited financial resources. Income rates are low. Conflict between resources needed for long-term planning to ameliorate present social deficit in the welfare of the population and adaptation planning Technological, Information and Science: Lack of basic information, observation and monitoring systems. Inefficiency in transmission of information to decision makers. Vulnerability and disaster risk reduction does not always lead to long-term adaptive capacity Social/Psychological/Cultural: Perception of risk. Lack of awareness of environmental changes and the implications for livelihoods Other: *[Need specifics/update from SOD]*		
Polar Region [Chapter 28]	Mainstreaming adaptation into existing policy processes and priorities.	*[Need specifics/update from SOD]*	*[To be completed post-FOD]*	Opportunities include changing resource bases, shifting land use and/or settlement areas, combining technologies with Indigenous knowledge, changing timing and location of hunting, gathering, herding, and fishing areas, and improving communication and education; providing hunter support programs; distribution of traditional foods between communities and the use of community freezers; for the permafrost, use of pile foundations, insulation of the surface, clearance of snow, adjustable foundations for	*Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Lack of national policies [28.4] Economic (Human and financial capital): *[Need specifics/update from SOD]* Technological, Information and Science: uncertainties of climate projections, lack of local downscaling combined with uncertainties in future economic, social and technological developments [28.4]. Lack of technical information and capacity. Lack of a systematic assessment of	Fauna unable or poorly able to cope with temperature increases of as little as 1-3°C [28.1]. Polar bears are likely not able to adapt in face of sea ice loss [28.2.2.1.2].	The most effective adaptation options will be those that recognize the nexus between adaptation and sustainable development. Adaptation to climate change occurs in the context of, and is inextricably linked to societal change; and climate is not the most important driver of vulnerability in polar communities nor is it rarely the sole or primary stimulus for taking adaptive action [28.4]

Region	*Framing*		*Rate of change*	*Opportunities*	*Constraint*	*Limits*	*Synthesis*
				smaller structures, and increased use of artificial cooling, selective forest regeneration, sustainable management of ecosystems	risks [28.4] Social/Psychological/Cultural: Other: *[Need specifics/update from SOD]*		
Small Islands [Chapter 29]	Mainstreaming and integrating climate change into development plans is seen as a goal.	Coastal adaptation and protecting coastal ecosystems and communities is of critical importance (29.7.2.1)	*[To be completed post-SOD]*	Building shoreline resilience, island building [29/6/2]	*Specific constraints include:* Structural: *[Need specifics/update from SOD]* Governance/Institutional: Lack of financial resources. Uncertain political and legal framework Economic (Human and financial capital): Lack human resource capacity. Technological, Information and Science: Lack of technology. Lack of climate change and socio-economic scenarios and data at the required scale. Social/Psychological/Cultural: Lack of cultural and social acceptability and Other: *[Need specifics/update from SOD]*	None identified.	Lessons learned from adaptation experiences in one island may offer some helpful guidance to other states, wholesale transfer may not always be advisable, as the 'lenses' through which adaptation options are viewed differ from one community to the next, based on ecological, socio-economic, cultural and political values [29.8].
Synthesis	*[To be completed post-SOD]*	*[To be completed post-SOD]*	*[To be completed post-SOD]*	*[To be completed post-SOD]*	[*To be completed post-SOD]*	[*To be completed post-SOD]*	[*To be completed post-SOD]*

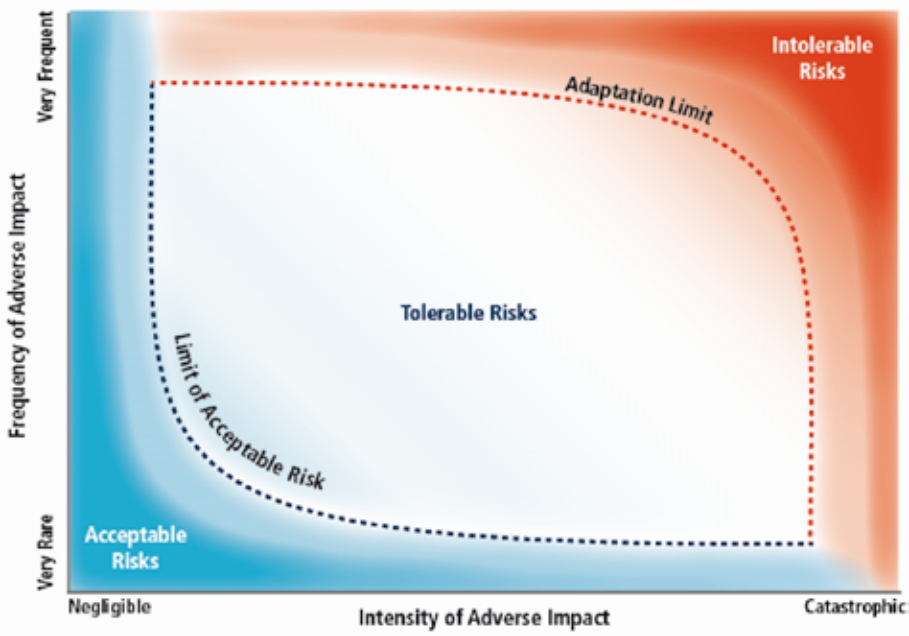

Figure 16-1: Conceptual model of the determinants of acceptable, tolerable and intolerable risks and their implications for limits to adaptation (Dow et al., 2013; after Klinke and Renn, 2002).

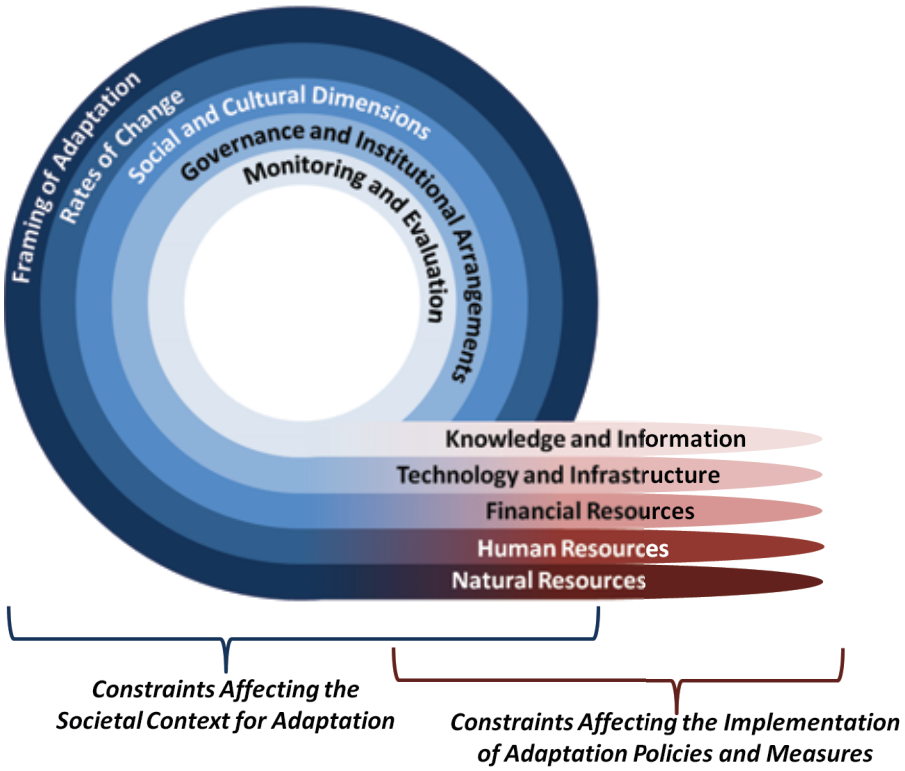

Figure 16-2: Identification of key adaptation constraints considered in this chapter, which are categorized into two groups. One reflects constantly evolving biophysical and socio-economic processes that influence the societal context for adaptation. These processes subsequently influence the implementation of specific adaptation policies and measures that could be deployed to achieve a particular objective.

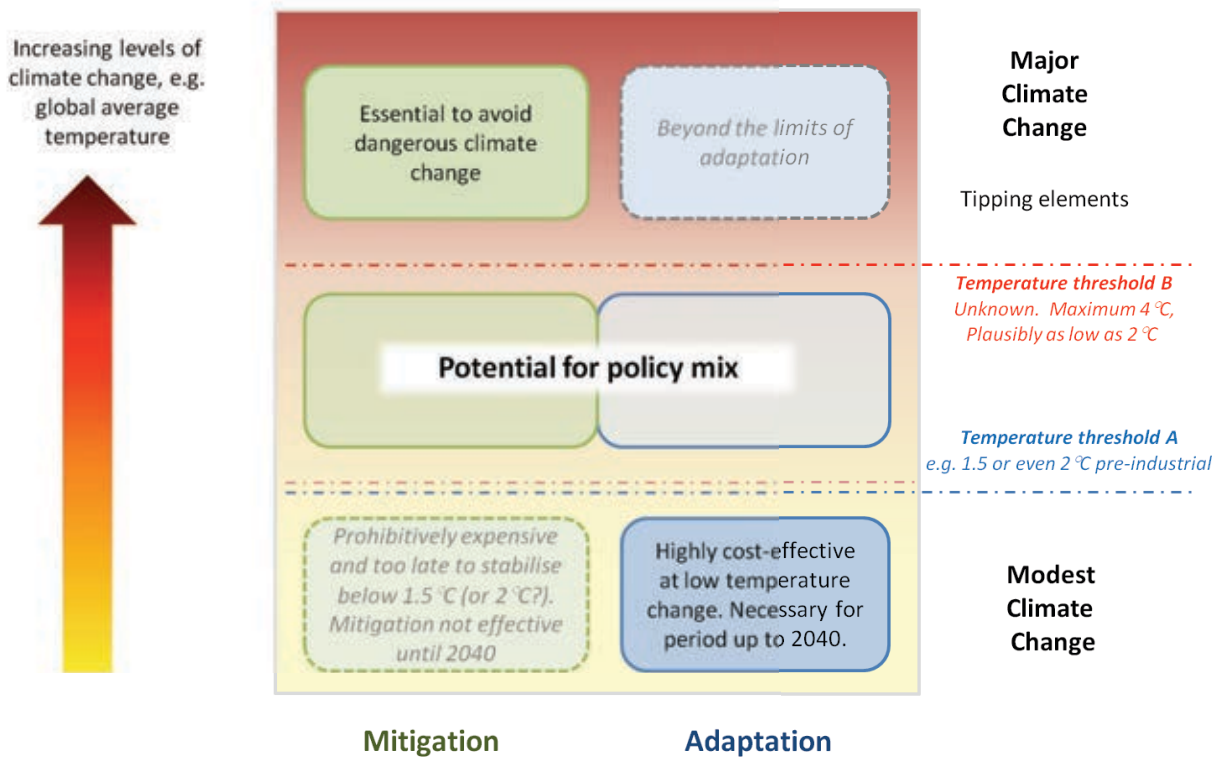

Figure 16-3: Adaptation policy space as a function of mitigation pathways (Watkiss et al., 2013).

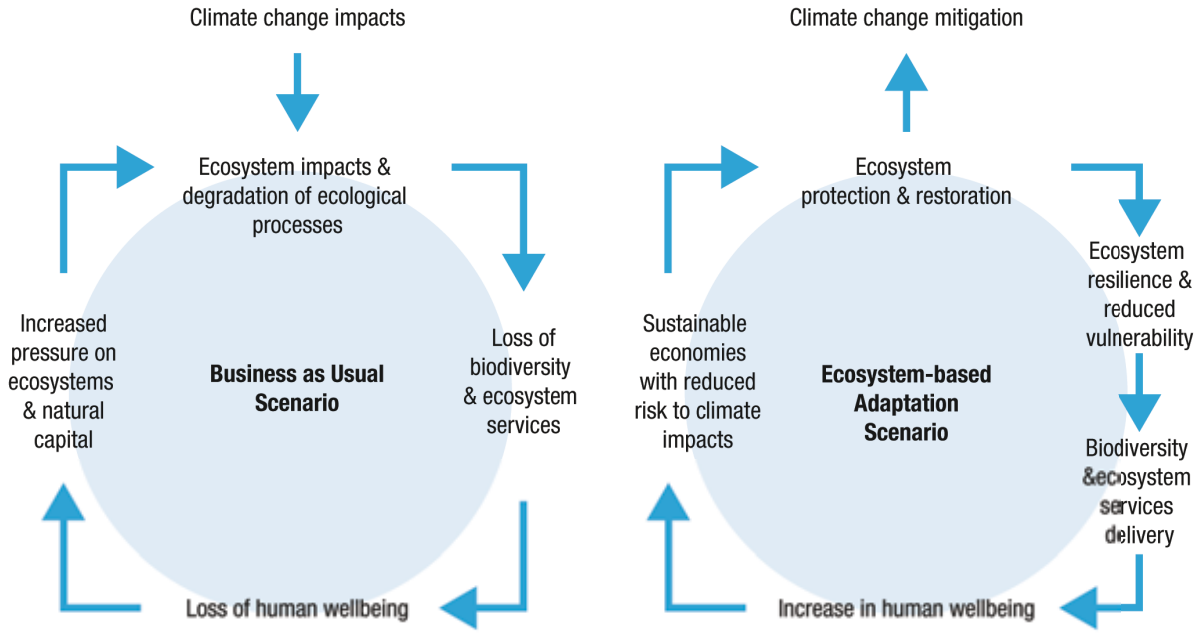

Figure EA-1: Adapted from Munang *et al*. (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.

Chapter 17. Economics of Adaptation

Coordinating Lead Authors
Myuyeye Chambwera (Zimbabwe), Geoffrey Heal (USA)

Lead Authors
Carolina Dubeux (Brazil), Stéphane Hallegatte (France), Liza Leclerc (Canada), Anil Markandya (Spain), Bruce McCarl (USA), Reinhard Mechler (Austria), James Neumann (USA)

Contributing Authors
Patrice Dumas (France), Samuel Fankhauser (UK), Alistair Hunt (UK), Howard Kunreuther (USA), Richard Tol (UK / Netherlands), Paul Watkiss (UK), Richard Woodward (USA), David Zilberman (USA)

Review Editors
Eduardo Calvo (Peru), Ana Iglesias (Spain), Stale Navrud (Norway)

Volunteer Chapter Scientist
Terrence Kairiza (Zimbabwe)

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References

Executive Summary

In the presence of limited resources and a range of goals, adaptation implies trade-offs between alternative policy goals *(high confidence)*. Economics offers insights into these trade-offs and into the wider consequences of adaptation. It also helps to explain the differences between the potential of adaptation and its achievement as a function of costs, barriers, behavioral biases, and resources available. [17.3.2, 17.3.3, 17.3.4] Economic analysis of adaptation is broadening from an emphasis on efficiency and market solutions to include consideration of inequities, non-market goods and services, behavioral biases, barriers and constraints, the consideration of ancillary benefits and costs, as well as decision-making processes including the notion of risk management. Impacts of climate change and of adaptation responses on the distribution of income and wealth, and on ecosystems and the goods and services that they provide, are increasingly recognized as important components of the overall picture that must be included in economic evaluations. [17.5.4, 17.3.6.3, 17.3.6.4]

Economics offers several types of insights into the following aspects of adaptation policy *(high confidence)*:

- The monetary dimension of costs and benefits [17.2.1]
- The assessment of non-market costs and benefits [17.2.1, 17.3.7.3]
- Estimation of the distributional consequences of adaptation and its impact on poverty [17.2.1, 17.2.7]
- The relationship between adaptation and development [17.2.7]
- The types of adaptation that will occur without centralized actions (autonomous or private adaptation) and those that require centralized support or direct public action (planned or public adaptation) [17.2.1]

- Approaches to the design of incentive systems that will encourage private adaptation [17.5]
- Situations where adaptation actions may totally or partially worsen climate change effects. [17.5.1]
- The impact of different value systems and ethical considerations on which adaptation options appear desirable [17.3.5]
- Although the theoretical basis for economic evaluation of adaptation options is clear, there is little experience of practical application of this approach to adaptation problems. There is however extensive experience of applying the concepts and methods underlying the economic framework in other contexts, which is useful for designing climate adaptation policies. [17.6.1].

Economics provides important inputs to the evaluation and ranking of adaptation options in the face of uncertainty (*high confidence)*. Approximate approaches are often necessary because of the lack of data or because of uncertainties about the nature of climate change or the efficacy of adaptation actions. A range of economic tools helps to address these uncertainties and helps design policies that are acceptable with a range of preferences and robust to existing uncertainties. There are methodologies that are able to capture non-monetary effects and distributional impacts, and to reflect ethical considerations. The resulting ranking depends on the "value system", i.e. on the weights attributed to different objectives. [17.2.6.1, 17.2.6.4, 17.3.5, 17.3.7]

Development and adaptation can be complementary or competitive and development can yield adaptation co-benefits, provided it takes into account climate change in its design. Adaptation actions can provide significant co benefits such as alleviating poverty and enhancing development especially in developing countries *(high confidence)*. Ancillary effects may be a source of market failure. Many aspects of economic development also facilitate adaptation to a changing climate, such as better education and health, and there are adaptation strategies that can yield welfare benefits even in the event of a constant climate, such as more efficient use of water and more robust crop varieties. Maximizing these synergies requires a close integration of adaptation actions with existing policies, referred to as "mainstreaming". [17.2.7, 17.4.4]

Existing incentives will lead to private adaptation actions. But public action to support adaptation is justified by the public goods nature of knowledge and much of the required infrastructure, by market failures, by the distributional impacts of climate change, and by behavioral biases. Economic instruments have high potential in fostering adaptation as they directly and indirectly provide incentives for anticipating and reducing impacts (*high confidence*). Instruments comprise risk sharing and transfer mechanisms (insurance), loans including public private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including land taxes, direct investment, norms and regulations, behavioral approaches and institutional innovations. [17.4, 17.5]

Risk financing mechanisms at local, national, regional, and global scales contribute to increasing resilience to climate extremes (*medium confidence*). Applicable mechanisms comprise informal and traditional risk sharing, such as relying on kinship networks, as well as market-based instruments including microinsurance, insurance, reinsurance, and national, regional and global risk pools. With considerable disaster insurance market failure, public private partnerships are the norm rather than the exception with the public sector acting as regulator, provider or insurer of last resort (*high confidence*). Price signals associated with risk financing can provide incentives for reducing risk, yet the evidence of effectiveness is weak and the presence of many counteracting factors actually often leads to disincentives, which is also known as *moral hazard*. [17.3.4, 17.3.6, 17.4, 17.5.1]

Estimates of the global costs of adaptation continue to improve, but remain inconsistent in methods, sectoral coverage, purposes, and time frames. The most recent estimates suggest a range from $75 billion to $100 billion per year globally by 2050, but important omissions from these estimates suggest the high end of this range could be much higher, and important shortcomings in the data and methods available for costing adaptation suggest the low end of this range could be substantially lower (*low confidence*).

- Defining the benefits and cost of adaptation is difficult, limited by data, and depends on value judgments. Estimating adaptation costs poses methodological, practical and moral difficulties, with consequences for how adaptation can be funded. [17.3.6.3, 17.3.6.4, 17.3.10, 17.3.11, 17.6]
- The existing estimates of global adaptation cost could be higher if sectors such as ecosystems, tourism, and socially contingent effects are included, and if the adaptation deficits of developing countries are more fully

taken into account. The global figures are based on only a few lines of evidence [17.6], and cover a selected number of sectors.

- Some evidence suggests that incremental adaptation costs increase over time as climate change unfolds (*low confidence*), but consideration of current adaptation deficits suggests that costs could be high in the short-term as well, and inconsistencies in the effect of economic development on adaptation capacity also confound the reliability of estimates of the trend over time [17.6.3].

Adaptation costing studies suffer from the absence of a robust community of practice, with great inconsistencies in the purposes, methods, data quality, and sectoral coverage of these analyses, limiting attempts to aggregate the finer-scale study results across regions and time [17.6.3]. Among these regional and local-scale analyses desirable characteristics include: a broad representation of relevant climate stressors to ensure robust economic evaluation; consideration of multiple alternative and/or conditional groupings of adaptation options; rigorous economic analysis of costs and benefits across the broadest possible market and nonmarket scope; and a strong focus on support of practical decision-making that incorporates consideration of sources of uncertainty [17.6.3]. Few current studies manage to achieve all of these objectives.

17.1. Background

This chapter assesses the literature on the economics of climate change adaptation, building on the Fourth Assessment Report (AR4) and the increasing role that economic considerations are playing in adaptation decision-making and policy. AR4 provided a limited assessment of the costs and benefits of adaptation, based on narrow and fragmented sectoral and regional literature (Adger *et al*, 2007). Substantial advances have been made in the economics of climate change after AR4. A key economic message from this literature is that the benefits of early action are greater than the costs of inaction. The literature also addresses the economic problem of climate change as a global market failure that is characterized by risk and uncertainty.

Adaptation action and policy has also advanced since AR4, and the literature on the economics of adaptation has reflected this. This chapter builds on other chapters in this assessment, in particular Chapter 2, which sets the basis for decision-making, recognizing economics as a decision support tool for both public and private actors. The type of economic approach used depends on factors discussed in Chapter 2 among others, including the agent making the decision, the nature or type of decision, the information used to make the decision, who implements the decision, others affected by the outcomes and the values attached to those outcomes. While realizing the linkages between adaptation and mitigation, the starting point of this chapter is that adaptation is a given need.

17.2. Adaptation as an Economic Problem

There are many adaptation strategies, and when considering these we need to judge whether the benefits outweigh the costs, with benefits and costs broadly defined. We have to consider current and future benefits, costs and resource usages, as well as uncertainty. Non-economic goals (concerning equity or environmental targets) are also of importance, as are efforts to achieve goals at highest net benefit or lowest net cost.

17.2.1. Reasons for Public Provision of Adaptation

Adaptation actions can be autonomous or planned. Some planned adaptations are public goods, which need to be put in place by elements of broader society (governments, NGOs, international organizations etc.). Their role exemplifies the classical economic definition of a public good, which is generally provided by an agency acting on behalf of a group of people. Economic analysis shows that market forces will under-provide such goods (Samuelson, 1954). Other reasons for public provision of certain adaptation measures include the existence of:

- Divergence between the social and private discount rates (i.e. different valuations of the future)
- Differences in risk aversion and risk perception between society and private individuals
- The value that society places on resolving inequities caused by climate change
- Possibilities for maladaptation where actions on behalf of one party worsen another's adaptation status

- Barriers to adaptation arising from lack of resources (human, financial, technical, etc.)
- Land ownership or property rights patterns that preclude private adaptation efforts on affected lands
- A desire to facilitate adaptation in unmanaged but highly vulnerable areas.

17.2.1.1. Broad Categorization of Adaptation Strategies

There are many possible adaptation actions, as indicated in chapters 14 and 15. In economic terms these include:

- Direct capital investments, including in infrastructure (e.g. dams and water management)
- Technology development through research (e.g. crop varieties)
- Creation and dissemination of adaptation information (through extension or other communication vehicles)
- Human capital enhancement (investment in education)
- Redesign of or development of new adaptation institutions (e.g. forms of insurance)
- Changes in norms and regulations to facilitate autonomous actions (e.g. building codes)
- Changes in individual behavior
- Emergency response procedures and crisis management

Not all adaptation involves investment or is costly. Some adaptation measures involve modification of recurring expenditures as opposed to new investments (replacing depreciated equipment with more adapted items). Sometimes it involves changes in behaviors and lifestyles (e.g. due to increased frequency of heat waves).

17.2.1.2. Broad Definition of Benefits and Costs

The consequences of adaptation decisions cannot be expressed comprehensively only through the standard economic accounting of costs and revenues. Adaptation decisions can also affect:

- Income distribution and poverty (Jacoby et al, 2011)
- Macroeconomic performance (see, e.g., Fankhauser and Tol, 1995);
- Allocation of funds with a crowding out effect on other investments (Hallegatte et al., 2007) and future technical progress (Hallegatte and Dumas, 2008)
- Welfare of current and future generations through non-monetary effects
- Changes in regional distribution of economic activity, including employment
- Alterations in non-market factors such as water quality, ecosystem function, and human health.

17.2.2. Toward a Realistic Assessment of Strategy Attractiveness

Adaptation cannot reasonably overcome all climate change effects (Parry et al 2009). Some adaptation options will simply be too costly (from now the words cost and benefit will be broadly used as discussed in 17.2.1.2). Additionally social and political willingness to act and scarcity of resources will limit strategy adoption and preclude complete adaptation. A conceptual way of looking at this for a given adaptation endeavor is in Figure 17-1.

[INSERT FIGURE 17-1 HERE
Figure 17-1: The narrowing of adaptation from suggested adaptations to what will be done. Forces causing the narrowing are listed in black.]

Figure 17-1 shows factors that will make the use of all adaptation strategies and complete adaptation impossible in a reasonable time scale. First, the sheer magnitude of the earth system suggests one cannot cancel all impacts (e.g., it is impractical to restore outdoor comfort under high temperatures). Second, certain processes (species extinction, melting of an ice cap) may be irreversible in any practical time period. Third, resource and knowledge availability plus uncertainty limits adoption. Fourth, adaptation measures may not be consistent with other policy objectives and priorities (i.e. competition for resources). Fifth, implementation barriers, obstacles, financial constraints and other market failures may constrain adoption (see Section 17.3).

17.2.2.1. Adaptation as a Dynamic Issue

Adaptation is not aimed at going from one stable situation to another. The challenge is to continually adapt to a "perpetually changing" climate (Hallegatte, 2009). Fundamentally adaptation is a long-term transitional process.

Many adaptations have long lasting effects like construction of seawalls or discovery of drought resistant crop genes. The optimal levels of investments with upfront costs and persistent benefits increase when the benefits are more long lasting or when climate change damages accumulate slowly (Wang and McCarl,2012). However, dynamic maladaptation is also possible as protecting now can expand investment in vulnerable areas and worsen future vulnerability (Hallegatte, 2011).

17.2.2.2. Funding Project-Based Adaptation

Adaptation to climate change is generally thought to be most efficient if it is mainstreamed into existing activities and processes (needs a reference). However, adaptation actions financed by external sources (e.g., multilateral or bilateral adaptation funds, research and development funds) are usually organized in discrete fixed-term projects that allow funders to monitor progress and adjust conditions if necessary. This raises difficult issues related to eligibility and potential co-funding, particularly in developing countries with a large "adaptation deficit" (Burton, 2004), where there are close links between adaptation to climate change, adaptation to natural climate variability and broader issues of socio-economic development. These links raise two central questions for defining eligible adaptation measures:

1) Is eligible adaptation restricted to measures that reduce the risks of anthropogenic climate change or are measures to reduce the risks of natural climate variability also included?
2) Is eligible adaptation restricted to measures that are motivated primarily by climatic risks or does it also include measures where reduction of such risks is only one of several benefits?

Based on these two questions definitions of adaptation range from very strict (definition 1) to very broad (definition 4) (Table 17-1).

[INSERT TABLE 17-1 HERE
Table 17-1: Four definitions of eligible adaptation.]

A strict definition of eligible adaptation may make it politically easier to motivate the need for international adaptation funding but risks excluding many efficient projects if they are not primarily motivated by climate change. A broader definition makes it easier to find projects that reduce current as well as future climatic risks but it risks losing the focus on adaptation and the associated political momentum for international funding. When a broad definition of adaptation is applied, co-financing by recipient countries may appear justified under certain conditions. The level of co-financing would depend on the relative importance of climate change compared to other reasons for a particular measure and on the resources that a country can reasonably provide itself (Füssel *et al.*, 2012). However, coherent criteria for measuring the fraction of an "adaptation project" attributable to anthropogenic climate change or for determining the level of co-financing requested for projects that address climate change adaptation jointly with other policy goals have not been developed so far. If adaptation funding is restricted to additional adaptation costs and primary funding comes from another external source, close coordination between both funders is required for practical reasons (Agrawala, 2008).

17.2.2.3. International Burden Sharing

Climate change is characterized by a "double inequity" (Stern, 2007) because those countries that are most vulnerable to climate change have generally contributed least (on a per capita basis) to causing it (Panayotou *et al.*, 2002; Tol *et al.*, 2004; Mendelsohn *et al.*, 2006; Patz *et al.*, 2007; SEGCC, 2007; Srinivasan *et al.*, 2008; Füssel, 2010). This asymmetry between responsibility and capability on the one hand and vulnerability on the other is

considered unjust based on concepts of justice that include the "no harm" principle and the polluter pays principle. This injustice implies obligations for countries with high responsibility and/or capability, and rights for countries with high vulnerability. The distinctive justice issues raised by international adaptation policy have recently gained a more prominent role in the scientific literature (Adger *et al*., 2006; Paavola and Adger, 2006; Miller, 2007; Heyward, 2007; Comim, 2008; Jagers and Duus-Otterström, 2008; Mearns and Norton, 2009; Klinsky and Dowlatabadi, 2009; Grasso, 2010; Harris, 2010; Inthorn *et al*., 2010; Füssel, 2011; Füssel *et al*., 2012).

The United Nations Framework Convention on Climate Change (UNFCCC) contains various provisions for financial support from industrialized countries to vulnerable developing countries but adaptation became really important in the UNFCCC negotiations only in 2001, when the 7th Conference of the Parties (COP 7) to the UNFCCC established three funds to support adaptation in developing countries. However, the rights and obligations related to adaptation funding were not clearly defined in the UNFCCC, leaving significant room for legal and political debates (Verheyen, 2002, 2005; Klein and Persson, 2008; Dellink *et al*., 2009; Klein, 2009; Persson *et al*., 2009; Hof *et al*., 2010; Füssel *et al*., 2012).

Important questions that are the subject of controversy in international negotiations on global adaptation funding as well as in academic debates are (Füssel *et al*., 2012):

- Who pays and how much into the adaptation fund based on which criteria?
- Who is eligible for receiving payments from the fund, and which criteria are used for prioritising recipients and for allocating funds?
- Which adaptation measures are eligible for funding, and what are the conditions and modalities for payment?
- How and by whom are decisions made?

While there is broad agreement that substantial payments are required from industrialized countries to support adaptation in developing countries, none of the questions above can be answered unequivocally based on legal or ethical considerations. Furthermore, these questions are not independent of each other as insufficient availability of funds can give rise to additional conflicts. In particular, efficiency and equality goals can be in conflict with each other if effective adaptation in one country is much more costly through no fault of their own (e.g. due to unfavourable geographical conditions) than in another country and the adaptation fund has insufficient resources to fulfil all justified claims (Füssel, 2011; Füssel *et al*., 2012).

17.2.3. Adaptation and Mitigation as Competitive or Complementary Investments

Adaptation and mitigation funding may need coordination. AR4 WGII chapter 18 presents a discussion of trade-offs and synergies. Often these are rival choices where investments in one might preclude those in the other. They also compete with consumption and non-climate investments. For example some adaptation strategies require land-use change as do both mitigation strategies and food production. Nevertheless the judicious use of adaptation jointly with mitigation lowers the total cost of climate change and implies a portfolio approach (de Bruin et al, 2009; Wang and McCarl, 2012, Koetse and Rietveld, 2012). Also mitigation reduces the uncertainty and magnitude of future changes in climate, making adaptation cheaper and thus more efficient (Hallegatte et al., 2010).

17.2.4. Inter-Relationships between Adaptation Costs and Residual Damage

In the climate change context, residual damages are those damages of that remain after adaptation actions are taken. Some literature has attempted to define residual damages more precisely. The U.S. National Academy of Sciences (2010), for example, distinguishes potential impacts (defined as "All impacts that may occur given a projected change in climate, without considering adaptation") from residual damages (defined as "The impacts of climate change that would occur after adaptation") Others have simply identified residual damages as those that remain after adaptation is implemented (World Bank 2010).

As an illustration of the relationship between adaptation cost and residual damage, Hallegatte *et al* (2011) conducted a study of the consequence for Copenhagen of sea level rise and the costs of adaptation, projecting mean annual losses as a function of the protection provided (see Figure 17-2).

[INSERT FIGURE 17-2 HERE
Figure 17-2: Illustrative example assuming a homogenous protection at 180 cm above current mean sea level (in the 'No SLR' and '50 cm SLR' cases). The vertical arrow shows the cost of SLR in the absence of adaptation. The horizontal arrow shows the need for adaptation to maintain unchanged mean annual losses.]

De Bruin et al (2009) and Hof et al (2009) have examined how increasing efforts lowers residual damages and formulate a model where adaptation actions are taken to the point that their marginal costs just offset marginal residual damages. Parry et al 2009 introduces unavoidable damages and Wang and McCarl (2012) study them, showing that higher degrees of unavoidable damages merit more mitigation but less adaptation effort.

17.2.5 Defining What Constitutes The Cost of Adaptation

Some define the cost of adaptation as simply the additional investment needed to adapt to future climate change (UNFCCC, 2007). But a full cost accounting needs to consider capital, operating, and nonmonetary costs of adaptation, considering metrics beyond those in monetary units. An economic approach would commonly take one of two definitions: 1) Costs of adaptation are the full range of costs incurred to undertake all appropriate adaptation measures; or 2) Costs of adaptation are the full range of costs incurred to restore economic welfare to pre-climate change levels (World Bank 2010). This would include the costs of fully implementing a given set of adaptation strategies including the opportunity cost of the funds used.

Defining an "adaptation project" and its cost raises conceptual issues. Many actions have an influence on the impact of climate change without being adaptation projects per se (e.g., enhanced building norms). Many "adaptation actions" have consequences beyond a reduction in climate change impacts. Defining the adaptation component (and cost and benefit) of a project requires the definition of a baseline (what would be the impact of climate change in absence of the adaptation action? What alternative project would be implemented in the absence of climate change?), and evaluation of the "additionality" of the project. For instance, action to adapt existing infrastructure to climate change are pure adaptation projects, and their cost can be considered as adaptation costs. The building of new infrastructure may be more costly because of climate and in that case only a fraction of their cost can be attributed to climate change and be labeled adaptation cost (See Dessai and Hulme 2007).

17.2.6. Methodological Considerations

17.2.6.1. Data Quality and Quantity

There is very little discussion on data gaps related to assessing the benefits of adaptation. Callaway (2004) suggests that a major challenge is the low quality and limited nature of data, especially in many developing countries. He also notes many transactions are not reported because they occur in informal economies and social networks. In a more general setting Hughes et al (2010) note that historical weather data is not typically sufficiently detailed while others note sparse data on costs of adaptation actions. For example, Bjarnadottie et al. (2011) note incomplete and contradictory data on house retrofit costs for hurricane protection. Also there are simply missing non market data on such items as recreational fishing as affected by climate and possible adaptation.

17.2.6.2. Costs and Benefits are Location-Specific

Calculating localized impacts requires detailed geographical knowledge of climate change impacts, but these are a major source of uncertainty in climate models (see J. C. Refsgaard & K. Arnbjerg-Nielsen & M. Drews & K. Halsnæs & E. Jeppesen, H. Madsen & A. Markandya & J. E. Olesen & J. R. Porter & J. H. Christensen (2013), The

role of uncertainty in climate change adaptation strategies—A Danish water management example Mitig. Adapt. Strateg. Glob Change, 18, 3, 337/359.). Compared with developed countries, there is also a limited understanding of the potential market sector impacts of climate change in developing countries.

17.2.6.3. Costs and Benefits Depend on Socio-Economics

It is sometimes assumed that climate will change but society will not (Pielke, 2007; Hallegatte et al 2011; Mechler and Bouwer, 2013). Future development paths affect climate change impact estimate, and can alter estimates from positive to negative impacts or vice versa. Some studies show higher growth rates raise hurricane vulnerability (Bjarnadottir, 2011). On the other hand, higher incomes allow the funding of risk-reducing policies.

17.2.6.4. Discount Rates Matter

Because adaptation costs and consequences occur over time, discount rates are a core question. Opinions vary sharply on this question (Baum, 2009, Beltratti Chichilnisky and Heal XXXX). Hof et al (2010) notes that a low discount rate is needed for distant future climate change to matter. A low discount rate is the primary reason for the relatively high estimates of climate damage in the Stern Review.

For climate adaptation projects, the social discount rate is the relevant one (Heal 2009). The rates used fall between 0.1 and 2.5%, although without good arguments for specific values (see Heal 2009). Nordhaus (2007) chooses a value of 1.5% while Stern uses a much lower value of 0.1%. Nordhaus emphasizes consistency with the rate of return on investment as a driving rationale while Stern points to ethical issues. Allowing environmental services to enter consumption can change the social discount rate substantially and generate a low or even negative social discount rate (Heal (2009), Guesnerie (2004) and Sterner and Persson (2007)). The UK Treasury now mandates the use of declining discount rates for long-term projects, as suggested by behavioral studies and by theoretical analysis (Arrow et al. 2012).

Weitzman (2007) treats differences in discount rates as different independent estimates of a true but unknown discount rate and points out that we should average different discount factors rather than rates, providing a case for a declining discount rate. Heal (2012) suggests that differences in discount rates reflect different value judgments and suggests they be resolved by a social choice procedure, perhaps by choice of the median rate. Wen (in: Bjarnadottir et al (2011)) investigates adaptation sensitivity against multi-hazards under discount rates varying from 0% to 9%. He proposes using a discount rate that decreases over time, as also recommended for longer term appraisals in the Green Book of the UK Treasury (from Hof et al, 2010).

17.2.7. Adaptation, Poverty, Equity, and Development

There is a relationship between adaptation actions and economic development actions, particularly in lesser-developed countries (see chapter 20). Development goals can be consistent with adaption goals, but not always. Many development projects enhance both adaptation and future development. For example, road construction practices that accommodate higher temperatures and more intense rainfall (World Bank 2009); agricultural investments that enhance heat tolerance and drought resilience (Butt et al. 2005, Strzepek et al. 2010); and public health investments that increase climate-enhanced disease resistance (Samet 2009, Markandya and Chiabai 2009). Development in general can make more resources available for adaptation.

A relevant question concerns whether economic development is a form of adaptation. SREX (IPCC, 2012) shows extreme event damages are ten times as large in developing areas as in developed areas and also that sustainable development can be threatened by climate change. Development generally diminishes vulnerability and raises adaptation capability (Schelling 1992, Schelling 1997, Tol 2005). However, development can also lead to increased vulnerability, for instance through urbanization of flood-prone areas (Hanson et al 2011). Furthermore better protection creates increased vulnerability to extreme events or protection failure (Burby 2001. Hallegatte 2012).

17.3. Decisionmaking and Economic Context for Adaptation

This section focuses on aspects of adaptation decisions making, individual interactions, and limits and obstacles to adaptation.

17.3.1. What are the Objectives of Adaptation?

The specific objectives involved in an adaptation effort can be diverse. One may try to cancel all impacts (negative and positive), maintaining the status quo. Alternatively one can try to cancel adverse impacts and capture positive opportunities, so that the welfare gain (or loss) is maximized (or minimized) as in IPCC (2007). These general objectives can be translated into operational rules and indicators for success in many ways.

Part of the literature presents adaptation as a continuous, flexible process, based on learning and adjustments. This branch emphasizes the need to preserve welfare, and opposes the static view of maintaining a status quo (IPCC SREX, Ch 8). Adaptation projects informed by this approach emphasize the role of learning and experimenting, plus the value of using reversible and adjustable strategies (Berkhout *et al*., 2006; Pelling *et al*., 2007; Leary et al., 2008; McGray et al., 2007; Hallegatte, 2009; Hallegatte et al., 2011c). Adaptation can also be "transformative', when achieving existing goals becomes impossible or undesirable, and changing goals becomes necessary (Stafford-Smith et al., 2011). Hunt and Taylor (2009) outline methods that could be used to model changes in future preferences, and provide examples addressing health and cultural heritage. Beltratti, Chichilnisky and Heal (1998) consider option values that arise as a result of uncertainty about future preferences.

17.3.2. Information, Transaction Costs, and Market Barriers

Transaction costs include the costs of accessing markets and information, along with reaching an agreement (Coase, 1937 and 1960; Williamson, 1979) and enforcement costs. Because of transaction costs, a mutually beneficial exchange may be impossible, and some adaptation actions may be impeded.

Certain publicly beneficial adaptation measures may not be privately beneficial due to such costs. Homeowners may not insulate homes due to transaction costs, whereas the collective benefit would be considerable (Hallegatte et al., 2007). This is a "market barrier" that appears even in absence of market failure (Jaffe et al., 2004).

17.3.3. Market Failures and adjustment costs

Adaptation may also face market failures such as externalities and moral hazards. As a consequence, some socially desirable actions may not be privately profitable. For example, construction may proceed in flood-prone areas even though this raises future social costs. In many countries flood plain risks are partly assumed by social insurance, transferring risk to the community (Burby et al., 1991, Laffont 1995). There are also externalities, since one household or firm located in a risky location may create higher social damages, for instance through the impact on supply chain (Tierney, 1997, and Henriet et al., 2012), thus requiring public norms and standards, tax measures or institutions in order to avoid such effects.

Significant (non-marginal) economic shifts and transitions involve significant adjustment cost driven by coordination failures and by factor immobility. There would be no adjustment costs if workers were able to move freely, firms were able to mobilize their fixed capital and technologies, and all economic actors had perfect information on the future. But experience with trade liberalization shows significant adjustment costs. We observe that this creates and destroys jobs in different sectors, but causes only limited intersectoral labor flows. In Brazil workers displaced from de-protected industries were only absorbed by other sectors with a several year lag (Muendler 2010). The same effects will be observed in the process of adapting to climate change.

17.3.4. Behavioral Obstacles to Adaptation

Economic agents adapt continuously to climate conditions, though not always using the available information, especially long-term projections (Camerer and Kunreuther, 1989) and consequences (Thaler, 1999, Michel-Kerjan, 2008). It has been observed for energy efficiency investments that households act in a way consistent with a very high discount rate of 20 to 100% (Train, 1985).

Also, individuals defer choosing between ambiguous choices (Tversky and Shafir 1992; Trope and Lieberman, 2003), a common situation regarding climate change adaptation. They systematically favor the status quo and familiar choices (Johnson and Goldstein, 2003). Also, individuals value profits and losses differently (Tversky and Kahnman 1974). In-depth studies show that these behavioral issues partly explain suboptimal household decisions (Shogren and Taylor, 2008, Gillingham et al., 2009), and lead to patterns of adaptation that are suboptimal.

17.3.5. Ethics and Political Economy

A difficulty in allocating adaptation resources is that there is no obvious choice of performance indicator (Füssel, 2010). Outcomes are often measured using indicators like GDP or cost benefit tests. But their limits are well known, (e.g., CMEPSP, 2009; OECD, 2009, Heal 2012) and include the failure to take into account resource depletion, environmental change, and distributional issues.

Distributional issues justify public intervention. Climate change impacts vary greatly by social group, and many have suggested that the poor are particularly vulnerable (e.g., Stern, 2006; Füssel, 2012). Some individuals, firms, communities and even countries may be unable to afford adaptation, even if it is in their own interest. Consideration of justice and fairness will play a role in adaptation option design (Pelling and Dill, 2009; O'Brien et al., 2009; Dalby 2009; Brauch, 2009a, 2009b; O'Brien et al., 2010b). The implementation of adaptation options may thus require taking into account the political economy of reforms and the addition of complementary policies to compensate losers (World Bank 2012).

Consequently, we must compare measures considering their equity implications. The traditional economic approach suggests choosing the most cost-effective projects and then resorting to financial transfers to satisfy equity objectives (Brown and Heal 1979: Atkinson and Stiglitz, xxxx). However this embodies strong assumptions including the ability to realize perfect and costless financial transfers. In more realistic situations the choice is not so clear cut. And in practical terms transfers are difficult to organize and may not be politically acceptable (Kanbur 2010). For example international development aid is often politically controversial (Bulir and Hamann, 2008). In these cases we have to resort to rankings that reflect both the net benefits and the impacts on equity.

17.3.6. Economic Decisionmaking with Uncertainty

17.3.6.1. Climate Change and Uncertainty

Decisions about adaptation have to be made in the face of uncertainty on items ranging from demography and technology to economic futures. Climate change adds to this with sources of uncertainty including:

- Uncertainty about the extent of future climate change (AR5, WGI report).
- Uncertainty about how climate change will translate into local impacts (AR5, WGI report).
- Uncertainty about the reaction of ecosystems and societies to climate change. An example is the ability of coral reefs to cope with warming.

The combination of uncertainty coupled with the long lifespan of a number of options leads to possible maladaptation. A distinction must be made between two types of maladaptation. An "*avoidable*" maladaptation situation arises from a poor *ex ante choice*. An "*unavoidable*" *ex post* maladaptation can result from entirely

appropriate decisions based on the information that was available *at the time*. An example is agricultural irrigation, where current investments to cope with a drying climate deplete water resources, resources that could facilitate later adaptation (Pfeiffer and Lin, 2010).

17.3.6.2. Comparing Adaptation Measures under Uncertainty

Next we consider methods to compare adaptation strategies under uncertainty. The first method is cost-benefit analysis under uncertainty where subjective probabilities are assigned to different climate futures (e.g., Tebaldi et al., 2005; New and Hulme, 2006). The "best" average project then will be the one that maximizes the average net present value of costs and benefits considering the probabilities. Risk aversion can be taken into account by seeking to maximize average income minus a risk-aversion measure times the variation in costs and benefits (or via an expected utility approach). It is also possible to implement a robust decision making approach that focuses largely on the worst possible outcomes, the so-called "maxi-min" approach. The cost-benefit approach also allows attribution of a higher weight to the poorest (Harberger, 1984).

Application of cost-benefit analysis requires evaluations in monetary terms. In many cases this is straightforward although these prices may need to be corrected for policies, monopoly power or other external factors distorting market prices (Squire and van der Tak, 1975). In cases where there are non-market items, a range of non-market valuation approaches (section ***17.3.6.3)*** can be adopted, but results are dependent on local conditions plus ethical and political choices.

When conducting cost-benefit analyses under uncertainty, an important concept is that of decision delay or option value (Henry 1974, Arrow and Fisher 1974). Indeed, when knowledge improves over time, it is possible to delay a decision and wait for more information. A key issue concerns irreversible actions, such as the destruction of a unique environment (Heal and Kristrom (2003)).

All these methods require probabilities for each climate scenario. However, these are difficult to determine, especially for low-probability, high-impact cases (Weitzman 2009, Kunreuther et al. 2012). Climate problems are in the realm of ambiguity rather than risk, meaning that while there is some information about relative likelihoods, this does constitute a probability distribution (Gilboa 2010). There is little work that applies such ideas to climate policy (see Henry and Henry, 2002, Millner et al 2010 and Kunreuther et al 2012). One approach is to work with a variety of physical models and posit probabilities that these models are correct. These alternative models can be thought of as scenarios.

In practice, a set of model scenarios is often the only available information. In this case, a scenario-by-scenario decision approach can be used (Lempert and Schlesinger, 2000; Ranger et al, 2010; Hallegatte et al 2012), looking for policies that are acceptable within a maximum number of scenarios. The aim is not to maximize the benefits within a scenario (or the average scenario) but to remain above the acceptable level for as many scenarios as possible. The most rigorous version of this method is the "maxi-min approach", in which we optimize for the most pessimistic scenario. The disadvantage can be that the most pessimistic hypothesis is highly unlikely.

17.3.6.3. Valuation of Non-Market Costs and Benefits

Cost-benefit analysis (CBA) of adaptation options often requires the valuation of non-market costs and benefits, i.e. the valuation of effects for which no value can be directly observed in a market. This is the case for impacts on public health, cultural heritage, environmental quality and ecosystems. The impacts of climate change on ecosystem services clearly have consequences for human wellbeing, both directly and through their impacts on economic activities. There has been progress in valuation of regulating, provision and cultural ecosystem services , as elaborated in the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB 2010) and Bateman et al (2011). There are two main categories of approaches to valuing ecosystem services; revealed and stated preference methods. As time and resources are scares when doing a CBAs we often resort to value transfer techniques (Navrud and Ready 2007). Brander et al (2012) applies value transfer to climate change

impacts on wetlands, which would be the benefits side of adaptation measures. For an overview see National Research Council 2004.

17.3.6.4. Examples of Multi-Metrics Decisionmaking for Adaptation

Multi-criteria analysis (MCA) is applicable to non-market impacts when valuation is impossible for theoretical or practical reasons. This approach does not require criteria to be measured in a common metric, but they must be weighted to reflect relative importance. Decision makers can include a full range of social, environmental, technical, and economic criteria—mainly by quantifying and displaying trade-offs. MCA is also useful when there is insufficient data for cost-benefit or cost-effectiveness analysis.

MCA approaches have been applied to adaptation issues including urban flood risk (Grafakos 2011; Kubal et al. 2009), agricultural vulnerability (Julius and Scheraga 2000) and studies on choice of options in the Netherlands (De Bruin et al. 2009; Brouwer and van Ek 2004), Canada (Qin et al. 2008) and Africa (Smith and Lenhart 1996). The UNFCCC developed guidelines for the adaptation assessment process in developing countries in which it suggests the use of multi-criteria analysis (UNFCCC 2002).

17.4. Ancillary Economic Effects of Adaptation Measures and Policies

In addition to creating an economy that is more resilient to the effects of climate change, adaptation strategies often have unintended ancillary effects of substantial importance. Ancillary effects also arise when investment funds devoted to mitigation or non-climate related investments in addition increase climate adaptation.

17.4.1. Broad Economic Consideration of Adaptation

In some cases adaptation strategies may be justified without detailed consideration of climate-related benefits because of ancillary benefits (these are sometimes referred to as “no regrets” strategies). Examples include:

- Sea walls that protect against sea level rise and at the same time will protect against tsunamis. However they also have co-costs causing damages to adjacent regions, fisheries and mangroves (Frihy, 2001);
- Crop varieties that are adapted to droughts and heat – will also raise productivity in the absence of climate change (Birthal et al, 2011);
- Better building insulation – which protects against heat will also reduce heating and cooling energy consumption (Sartori and Hestnes, 2007) and mitigate greenhouse gas emissions;
- Public health measures targeted at insect-borne diseases whose range will expand in a warmer world – will also have health benefits at present (Egbendewe-Mondzozo et al, 2011);
- More efficient use of water –adaptation to a drier world- will also yield benefits under current conditions of water scarcity. Development of lower-cost desalination methods have the same merits (Khan et al, 2009);
- Locating infrastructure away from low-lying coastal areas provide adaption to sea level rise and will also protection against tsunamis and storm surges;
- Afforestation and reforestation may improve adaptation of land production and will also both mitigate by carbon sequestration and benefit society by securing soil and reducing water run-off (Pattanayak et al,2005);
- Reducing the need to use coal-fired power plants though energy conserving adaptation will also provide mitigation , improve air quality and reduce health impacts (Burtraw et al, 2003).

17.4.2. Economic Consideration of Ancillary Effects

Suppose that a country has a fixed sum of money to allocate between two competing adaptation projects, each showing diminishing returns. To maximize benefits the funds should be allocated so that the marginal returns to each activity are the same. If both strategies generate positive ancillary effects not captured by the actor undertaking

the adaptation, then the socially optimal allocation of adaptation investment will differ from the private optimum and will favor the activity with the larger ancillary effects. Elbakidze and McCarl (2007) argue that it may be best to disregard ancillary effects because of the complexity of a complete analysis and the fact that in the settings they examine ancillary effects are roughly of the same magnitude. Viguie and Hallegatte (2011), Kubal et al. (2009), De Bruin et al. (2009), Brouwer and van Ek (2004), Ebi and Burton (2008), Qin et al. (2008), among others argue the contrary.

Equally important, and more difficult, is determining how much should be spent in total on adaptation versus other investments – mitigation, other aspects of development. For the best possible outcome the marginal social returns to all forms of expenditure should be the same, if appropriate, allowing for distributional impacts by differentially weighting benefits and costs to different income groups (Brent, 1996; Musgrave and Musgrave, 1973). In practice governments try to achieve this by setting a target rate of return for all public expenditures: if the marginal returns in all areas are equal to this then the equality of marginal rates is assured (Atkinson and Stiglitz, 1980; Starret, 1998)

17.4.3. Adaptation and Development Pathways

Adaptation is often considered on a project by project basis. In this "stand-alone" framework, adaptation actions are additional policies, and they are not included in other policies, such as development or economic policy. This is for instance the approach followed by the "National Adaptation Programmes of Action" of the UNFCCC (2002). Another vision is considering adaptation as an additional objective of development, which influences development policies (Klein et al. 2005; Füssel, 2007; Kok and De Coninck, 2007; O'Brien et al., 2012). This broader approach is often referred to as a "mainstreaming" of adaptation in public policies, in which all public policies need to take into account climate change and adaptation objectives. It is consistent with other trends in environmental policies that integrate risk management policies within development policies (Kellenberg and Mobarak, 2008; UN-ISDR 2009; World Bank and UN 2011), and climate mitigation polices now approached more as a low-carbon development issue than as a purely environmental issue (Stern, 2006; World Bank 2010).

17.5. Economic and Related Instruments to Provide Incentives

With the exception of insurance-related instruments there is relatively little literature on the use of economic instruments for adaptation. One reason is that, apart from insurance, few adaptation instruments work directly via economic incentives and through the use of markets. The potential of economic instruments in an adaptation context is, however, recognized. Agrawala and Fankhauser (2010) distinguish the following incentive-providing instruments relevant for key sectors: (i) Insurance schemes (all sectors; extreme events), (ii) Price signals / markets (water; ecosystems), (iii) Financing schemes via public private partnerships (PPPs) or private finance (flood defence, coastal protection, water); (iv) Regulatory measures and incentives (building standards; zone planning); (v) Research and development incentives (agriculture, health).

17.5.1. Risk Sharing and Risk Transfer, including Insurance

Insurance-related mechanisms can directly lead to adaptation and provide incentives or disincentives, which may involve formal and informal mechanisms. Informal mechanisms include reliance on national or international aid or remittances, and while such mechanisms are common, they tend to break down for large, covariate events (Cohen and Sebstad, 2003). Another informal mechanism is the inclusion of climate change risk under corporate disclosure regulations (National Round Table on the Environment and the Economy, 2012). Formal mechanisms include insurance (including micro-insurance), reinsurance, and national, regional and global risk pooling arrangements. Insurance typically involves ongoing premium payments to an insurer / reinsurer or the financial markets in exchange for coverage and post event claim payments (UNISDR, 2009). Markets differ substantially according to how liability and responsibility is distributed (Botzen et al., 2009; Aakre et al., 2010), and in many instances governments play a key role as regulators, insurers, or reinsurers in developed and developing countries alike (Linnerooth-Bayer et al., 2005). Insurance penetration in developed countries is considerable, whereas it is low in

many developing regions (Linnerooth-Bayer et al., 2011). In 2010 globally about 30% of disaster losses and 20% of climate related losses were insured.

Insurance-related instruments may directly and indirectly lead to adaptation. Two direct channels can be distinguished: i) instruments provide claim payments after an event, and thus reduce follow-on risk and consequences; (ii) they alleviate certain pre-event risks and allow for improved decisions (Skees et al., 2008; Hess and Syroka, 2005; Hoeppe and Gurenko, 2006). As one interesting example, using crop micro insurance linked to loans, farmers exposed to severe drought in Malawi were able to grow higher-yield, yet higher-risk crops, which allowed them to increase incomes (Linnerooth-Bayer and Mechler, 2011).

Indirect effects also exist. Premiums for risk coverage can provide an incentive to reduce the premium by reducing the risk. For example, differential UK flood insurance premium pricing offered according to flood zones has been effective in deterring new construction in high risk areas (Kunreuther and Michel-Kerjan, 2009; Kunreuther) and the National Flood Insurance program (NFIP) in the US requires communities to reduce risks before homeowners can access insurance for their homes (Surminski, 2010)

Developing countries are beginning to pool risks and transfer portions to international reinsurance markets. The Caribbean Catastrophic Risk Insurance Facility (CCRIF) set the precedent by pooling risks basin wide, thus reducing insurance premiums against hurricane and earthquake risks (World Bank, 2007). Similar schemes are under development and planning in Europe, Africa and the Pacific (Linerooth-Beyer and Mechler 2011).

The incentive effect is typically rather weak since decisions regarding risk prevention and adaptation are often influenced by many diverse factors. Kunreuther et al. (2009) found that insurance decisions are not based solely on costs and premiums, but also desires to reduce anxiety, comply with mortgage requirements, and satisfy social norms. Further, purchasing insurance may reduce adaptation with insured agents reducing their risk-minimizing efforts after taking out coverage. This is termed moral hazard and has been found to be rational for agents given the financial security provided by the contract (Kunreuther, 1996). Ultimately, this may increase maladaptation over time (Rao and Hess, 2009). Under-insurance can also arise when agents expect that the public sector will provide disaster assistance. Some refer to this as the Samaritan's dilemma (IMF, 2008).

17.5.2. Incentive Design

Through regulations, subsidies and direct intervention, there are many opportunities for policy makers to encourage autonomous adaptive responses to climate change. However, these efforts need to be designed so that they lead to efficient, cost effective responses while avoiding perverse results that run counter to the policy maker's objectives. A basic principle of designing efficient policies is that they affect the behavior of those who have the most to gain. For this reason, economists tend to favor policies based on voluntary actions influenced by incentives, either positive or negative, over mandates or uniform policies. Examples of these include water markets and various Payments for Environmental Services (PES), which are discussed in 17.5.4. A second consideration is cost effectiveness, i.e. the extent to which governments make the best use of their resources. The measurement of the net effect of a policy is challenging because it is difficult to anticipate what would have occurred in the absence of the policy.

Finally, policies must be carefully designed to avoid perverse outcomes that actually run counter to the policy maker's objectives. A classic example of this is found in policies that encourage adoption of water-saving technology in arid regions. Pfeiffer and Lin (2010) review cases where subsidizing irrigation water conservation actually leads farmers to increase total water use as they respond to greater efficiency by increasing the acreage under irrigation, an example of what is often called the rebound effect (Roy, 2000) whereby increases in efficiency of resource use result in more being demanded. In general it is best addressed by increasing the price of the scarce resource when efficiency gains from technological developments increase demand without increasing the supply of the scarce resource.

17.5.3. Loans, Public Private Finance Partnerships

The private sector has long been involved in the provision of public goods through Public Private Partnerships (PPPs). The rationale for governments is to reduce their financial cost by leveraging private funding, as well as to reduce the financial and operational risks involved in carrying out projects. Key instruments comprise public contracts, service concessions, public loan guarantees and concessional loans (Bräuninger et al. 2011). PPPs have been widely used for large infrastructure projects, one relevant example being the Thames flood defence barrier which protects London and the Thames estuary from tidal surges and coastal flooding. Finance was generated entirely by taxpayers, yet design, building supervision and construction were outsourced to the private sector (Bräuninger et al. 2011).

17.5.4. Payments for Environmental Services

Environmental services (ES) can contribute to adaptation (Millennium Ecosystem Assessment (2005), Daily (1997) and Heal (2000)). Payments for environmental services (PES) are a popular market-based approach that has been applied increasingly to translate external, non-market environmental services into financial incentives for preservation (Wunder et al, 2008; Wünscher et al, 2008; Engel et al, 2008). Those who stand to lose from decisions resulting in ES loss could choose to provide incentives for decision makers to adopt practices that ensure the continuation of the ES (Engel et al., 2008).

PES approaches in developing countries have met with mixed success. Focusing on payments for watershed services, Porras et al (2008) identified 50 ongoing schemes, 8 advanced proposals and 37 preliminary proposals. However it has been found that structuring the schemes is difficult when the services are hard to define (such as biodiversity) and where the scheme is driven more by government objectives and less by local needs. In such cases payments often do not guarantee the environmental improvements in spite of large outlays.

There are ample cases of mitigation–focused PES schemes (e.g. Wunder and Borner (2011), Pagiola (2008), Wunder and Albán (2008)), and more recently emerging evidence of the use of PES adaptation approaches. (Butzengeiger_Geyer et al., 2011; Schultz, 2012). Potentially well designed PES schemes they offer a framework for adaptation. Chishakwe *et al* (2011) draw comparisons and find synergies between PES community based natural resources management approaches in Southern Africa and community-based adaptation.

17.5.5. Improved Resource Pricing (Water Markets)

Studies of water sector adaptation often begin by citing the prospect of future water shortages and the potential for conflict among sectors (and sometimes among nations). One technique frequently cited for resolving these conflicts is the establishment of water markets and pricing schemes (e.g., Alavian et al. 2009; Vorosmarty et al. 2000, Adler, 2009). Traditionally water markets facilitate transfer from lower to higher-valued uses (Olmstead, 2010). A few studies make the case that water markets and pricing lower the impacts of climate change (Medellin-Azuara et al. 2008). In the most extreme cases, the projected increase in climate-induced water demand (particularly in the agriculture sector), coupled with a projected decrease in water supply, suggests that water supply/demand adaptation can only be achieved by a choice between water rationing and water pricing.

Many countries have instituted structures for water pricing in the domestic and agricultural sectors. Nevertheless tariffs for water are unevenly applied, collection rates are low, metering is rarely implemented (at least for the agricultural sector, which is typically the largest water user) and pricing structures are often based on annual rather than usage-based fees (Saleth et al.,2012). In a number of countries, there remain a number of important institutional barriers to water markets and pricing. These include a lack of property rights, limits on transferability, legal and physical infrastructures, affordability issues, and institutional shortcomings (Saleth et al. 2012) coupled with issues involved with return flows, third part impacts, market design, transactions costs, and average versus marginal cost pricing, (Griffin, 2012).

17.5.6. Charges and Subsidies including Land Taxes

The environmental economics literature over the past 30 years has emphasized the importance of market-based instruments (MBIs) relative to command and control regulations. MBIs are shown to be generally more cost effective, providing stronger incentives for innovation and dynamic efficiency. Within the wide range of instruments that qualify as market based, there is a general preference in terms of overall efficiency for axes over subsidies (Sterner, 2002; Barbier and Markandya, 2012).
In many cases climate change exacerbates the effects of pricing resources at below their social costs. This is true for some forms of energy (e.g. hydro) as well as most of the ecosystem services like water, genetic materials, pollination, erosion control and soil retention. If these resources were better priced, the need for additional public sector adaptation measures would be lessened.

In addition to the instruments already identified, others that are potentially important include: raising the price of energy through a tax (Sterner, 2011), developing markets for genetic resources (Markandya and Nunes, 2012) and strengthening property rights so schemes such as PES can be more effective. While the case for such social cost pricing through the use of charges is strong, it also has its limitations. Higher prices for key commodities can hurt the poor and vulnerable.

17.5.7. Behavioral Approaches

Because individuals fail to take into account properly low-probability risks (Tversky and Shafir 1992), and because they do not weigh long term consequences consistently (Ainslie 1975), taking into account behavioral biases can increase the efficiency of policies. For instance, people differently react to abstract information on distant events, versus concrete, emotionally-charged information linked with real-world experience (Trope and Liberman, 2003). In practice, this limits the impact of “dry”, emotion-free, information such as information on flood return periods (Fischhoff et al., 1978; Slovic, 1997). It is well documented that individuals do not use available information on natural risks when they make their choices (Magat et al., 1987; Camerer and Kunreuther, 1989; and Hogarth and Kunreuther, 1995). In the case of disaster risk management and risk awareness, it is well established that communication is more efficient if it goes beyond informing on probabilities and risks and provides information on how to react, using specific examples and real-world stories. Moreover, people usually overreact in the aftermath of a rare event (Weber et al. 2004), leading to biased and under-optimal responses (Hallegatte, 2011).

17.5.8. Intellectual Property Rights

Technology transfer is increasingly seen as an important means of adaptation. Christensen et al. (2011) in a Technology Needs Assessments carried out in developing countries list about 165 technological needs. In many of these cases patents and other intellectual property protection constrain technology transfer. Patent buy-outs, patent pools, compulsory licenses and other open source approaches have been used to relax this constraint (Dutz and Sharma, 2012). Patent buy-outs involve third parties (e.g. international financial institutions or foundations) acquiring the marketing rights for a patented product in a developing country. Patent pools represent a group of patent holders who agree to license their individual patents to each other (closed pool) or to any party (open pool). Compulsory licenses are issued by governments and allow patent rights to be overridden in critical situations. It is suggested that limits to technology transfer are limiting climate change adaptation (Henry and Stiglitz, 2010).

Health is one of the areas where adaptation to climate change will be required, and where developments in vaccines and treatments for vector borne diseases could be important. Hence these mechanisms for addressing IPR issues are directly relevant here. A similar approach can be applied in other areas such as seeds in drought prone or saline environments, water management technologies, pest management techniques etc.

17.5.9. Innovation, R&D Subsidies

Subsidies may be employed to encourage adaptation investments as well as behavioural change (Bräuninger at al., 2011). Subsidies involve direct payments, tax reductions or price supports that enhance the rewards from the implementation of an activity (Gupta et al., 2007). There has been some criticism of the efficiency of subsidies in terms of rent seeking and adverse effects on competitiveness (Barbier and Markandya, 2012); yet they are popular with decision-makers and the wider public. Subsidies are today mostly used for reasons other than climate adaptation, and evidence regarding its use for adaptation as well as regarding the incentivizing of adaptation R&D specifically is missing.

17.6. Costing Adaptation

Interest in estimating the costs of adaptation has grown as the need for action has become clearer. The literature focuses on two levels of costing: 1. global scale estimates, largely to assess the overall need for adaptation finance funds; and regional and local-scale estimates, often limited to a particular vulnerable economic sector, which may be applied to inform budgeting or to support adaptation decision-making, or to allocate scarce resources among the best prospects for effective adaptation.

17.6.1. Review of Existing Global Estimates: Gaps and Limitations

There have been a limited number of global and regional adaptation cost assessments over the last few years (World Bank, 2006; Stern, 2006, Oxfam, 2007; UNDP, 2007, UNFCCC, 2007; 2008; World Bank, 2010). These estimates exhibit a large range and have been completed mostly for developing countries. The most recent global adaptation costs range from $75 to more than $100 billion annually by 2050 (Table 17-2).

[INSERT TABLE 17-2 HERE
Table 17-2: Estimates of global costs of adaptation.]

IPCC (2012) considers confidence in these numbers to be *low*. The World Bank (2006) estimates the cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA), as does the Stern Review (2006), Oxfam (2007) and UNDP (2007). UNFCCC (2007) calculated existing and planned investment and financial flows required for adaptation. The World Bank (2010a) followed the UNFCCC (2007) methodology but included more extensive modeling as opposed to developing unit cost estimates, constructing marginal cost curves and climate stressor-response functions for adaptation actions, and included maintenance and coastal port upgrading costs.

Given their common approaches these estimates are interlinked, which explains the seeming convergence of their estimates, as discussed by Parry et al (2009). However there are important differences in terms of sectoral estimates, as Figure 17-3 shows in comparing the UNFCCC (2007) and World Bank (2010) studies. Extreme events, a potential source of large adaptation costs, are not covered by UNFCCC (2007), but are partially covered in the World Bank (2010) study and take into account a limited set of adaptation options. Parry et al. (2009) consider the UNFCCC (2007) estimates a significant underestimation by at least a factor of two to three plus omitted costs in ecosystem services, energy, manufacturing, retailing and tourism. They argue these estimates are low, based mostly on low levels of investment due to an existing adaptation deficit in many regions. Thus the numbers have to be treated with caution. There are a number of gaps, challenges and omissions associated with those global estimates that merit further discussion.

[INSERT FIGURE 17-3 HERE
Figure 17-3: Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges, crosses point estimates.]

The practical challenges of conducting global adaptation cost studies are apparent in the literature. The broad scope of these studies limits the analysis to few climate scenarios, and while the scenarios might be strategically chosen it is difficult to fully represent the range of future adaptation costs across all sectors. The broad scope also limits comprehensive consideration of adaptation options, non-market and co-benefits, equity issues, and adaptation decision-making (such limitations also apply to local and regional scale studies see Section 17.6.3). The global studies, designed to reflect the best available methods and data for the purpose of estimating the magnitude of the global economic adaptation challenge, achieve this limited goal but must be interpreted in light of these important limitations and uncertainties.

17.6.2. Consistency between Localized and Global Analysis

Adaptation costs and benefits are derived to inform specific investment decisions, generally at national and local levels, or to derive a "price tag" for overall funding needs for adaptation (generally at a global level). Given these different purposes it is difficult to compare "local", i.e, national and sectoral, with global numbers. The quantity/quality of local studies also varies by sector with more treatment of adaptation in coastal zones and agriculture. Less is known and many gaps remain for sectors such as water resources, energy, ecosystems, infrastructure, tourism and public health. Also assessments have predominantly been conducted in a developed country context (see Table 17-3 for examples of costs and benefits assessment).

[INSERT TABLE 17-3 HERE
Table 17-3: Coverage of adaptation costs and benefits.]

However, as Fankhauser (2010) notes, with the sole exception of coastal protection costs, adaptation costs have shown little convergence locally or in terms of sectoral to global costs. Fankhauser suggests that the global cost estimates using the I&FF methodology estimate the "true" costs of adaptation. The World Bank (2010) study uniquely takes a two-track approach doing parallel national (7 cases) and global adaptation estimates. For a number of country studies (Bangladesh, Samoa and Vietnam) a cross-country comparison of local and global adaptation costs was made, with the costs in terms of GDP found to be in reasonable agreement. Costs for strengthening infrastructure against windstorms, precipitation and flooding were about 10-20% higher compared to disaggregated global estimates, largely owing to the ability of country-level studies to consider at least some socially contingent impacts (World Bank 2010b, 2010c, 2010d). Further, there is evidence of under investment in adaptation with global estimates of the need for agricultural adaptation funds variously estimated in the range of $10-40 billion annually, but with actual expenditures in 2011 estimated at $244 million (Elbehri et al, 2011)

17.6.3. Selected Studies on Sectors or Regions

Now let us address studies that focus on costs and benefits of specific adaptation strategies. This section focuses on studies that illustrate the current state-of-the-art, with a particular focus on support of adaptation decision-making through economic analysis. Within that class of work, there are two broad categories of economic analyses of adaptation at the sectoral level: econometric and simulation approaches.

Econometric studies generally looks at past adaptations that have happened across climate regimes and relies on historical cross-sectional, time series, or panel data to infer the effects of adapting to climate across space or time. Within the econometric category, there are Ricardian studies (which relate to land values, or to profitability, e.g., Mendelsohn et al 1994, Deschenes and Greenstone (2007)) and more generic correlational approaches (e.g., Schlenker et al. (2005) linking temperature and precipitation to crop yields and in the livestock sector Seo and Mendelsohn (2008)). Both can be used to estimate the marginal effect of climate on impacts, incorporating adaptation, and in some cases they can infer types of adaptation strategies employed.

The simulation approach traces costs and benefits of adaptation strategies through mechanisms of interest, typically through a series of climate-biophysical-behavioral response–economic components. Within simulation modeling there are two main threads in the behavioral response/economic component of the simulation. The first involves

rational actors who consider the benefit and cost consequences of their choices and pursue economically efficient adaptation outcomes, and the second involves a decision-rule or reference based characterization of the response of actors to climate stressors (Dinar and Mendelsohn, 2011; Schlenker et al, 2005). As noted below, in many sectors the state-of-the-art begins with the simpler decision-rule based approach, and may progress to consider benefits and costs, and then perhaps to consider other factors, such as equity and nonmarket values.

The key advantages of an econometric approach are reliance on real-world data, "natural experiments" in some cases, and an ability to reflect the joint costs and benefits of multiple adaptation strategies to the extent they are employed together in real world. The econometric approach does not require the analyst to simulate all adaptation mechanisms, only to establish that there is a robust relationship is between a climate stressor and the outcome of interest. The data required to implement the approach, at its simplest level, are limited to seasonal climate and economic output and may be more generally consistent with current availability in many countries, so the approach also has the advantage that it can be applied broadly. The key disadvantages of the Ricardian approach are an inability to trace transmission mechanisms of specific adaptation measures or to isolate the marginal effect of these strategies or measures; the inability to transfer estimates out of context (e.g., an African study does not apply to Asia, where the climate, adaptation, and social context all differ and affect the marginal costs and benefits of adaptation measures); and that the statistical estimation can be challenging and sometimes subject to multiple interpretations (Schlenker et al (2005)). Finally, the econometric approach is limited in its ability to consider adaptive actions that are beyond the scope of current observations, particularly actions that might prove beneficial in responding to large increases in extremes or even changes in carbon dioxide concentrations that have not been experienced in the historical record.

Simulation modeling can be demanding – a key disadvantage – as it requires extensive data inputs and careful calibration. It is often not appropriate where data are sparse, and requires that models be available for the task. The payoff is that the modeling system can estimate the incremental change in crop output and water supply in response to changes in climatic conditions and agricultural and water resource management techniques. A further advantage of the simulation approach is that it provides an opportunity for stakeholder involvement at several stages of the analytic process: designing scope, adjusting parameters, selecting inputs, calibrating results, and incorporating adaptation measures of specific local interest (Dinar and Mendelsohn, 2011).

A separate issue from the benefit and cost estimation method is the perspective adopted with respect to the goals of adaptation. Some studies adopt the perspective that the goal of adaptation should be restoring pre-climate change (or current) level of service: these studies are typically for sectors where the analytic tools are in their infancy. Major drawbacks include implicit assumptions that current service can be restored without residual impacts, and the lack of attention to whether restoration is a cost-effective response. The alternative and typically more mature perspective involves an economic evaluation within the study that compares costs and benefits of adaptation options, and their distributional consequences. Such an approach implicitly acknowledges that planners have a choice along a broad continuum concerning whether to invest in adaptation or tolerate impacts and/or residual impacts. The decision-making framework can focus not only on whether to adopt an adaptation measure, but also the scale or extent of its implementation (e.g, how much sand to place on a beach to protect a dune from sea-level rise and storm surge). A potential drawback of this approach is the difficulty in knowing and estimating all costs and benefits of adaptive measures or suites of measures.

There are a wide range of studies available that attempt an economic evaluation of adaptation options. From these, several desirable characteristics can be identified. Namely such studies should contain:

- A broad representation of climate stressors, including both gradual change and extreme events, spanning multiple future outcomes((GCM) forecasts and greenhouse gas emissions scenarios). Consideration of multiple outcomes reflects forecasting uncertainty and can help to ensure the adaptation rankings that result are robust across a range of future outcomes (Lempert and Kalra 2009, also see Chapter 2).
- Representation of a wide variety of alternative adaptation responses (for example, in the agriculture sector, consideration of changes in crop varieties and farmer education to ensure the varieties are grown with the best available know-how). Depending on the context, single adaptation response with variation in dimension may be useful (for example, varying the height of a levee or the capacity of a dam spillway) (World Bank 2010, Fankhauser 2010, Fankhauser et al. 1999).

- Rigorous economic analysis of costs and benefits, which ideally includes consideration of market, nonmarket, and socially contingent implications; one-time and replacement capital and ongoing recurring costs; and costs of residual damages after an adaptation response is implemented (Watkiss 2011b).
- A strong focus on adaptation decision making, including a clear exposition of the form of adaptation decision-making that is implied in the study, and consideration of both climate and non-climate sources of uncertainty (Lempert et al. 2006, also see Chapter 2).

Table 17-4 highlights a select group of studies chosen to illustrate some of these characteristics. The studies include both simulation studies of the economic implications of adaptation options, and econometric ones which examine choices that producers make to adapt. These studies generally fall in the category of positive economics, where economic tools and analysis are used to examine the implications of alternative choices without imposing values of the author (see Friedman (1953)). A few studies incorporate a normative perspective, either explicitly or implicitly, reflecting value judgments of authors or study participants.

[INSERT TABLE 17-4 HERE
Table 17-4: Studies illustrating economic evaluation of adaptation options.]

Frequently Asked Questions

FAQ 17.1: Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision-making in this area?

Economic methods have been developed precisely to address decision-making in the face of uncertainty. Indeed some of these have already been applied to the evaluation of adaptation measures such as decisions on which coastal areas to protect and how much to protect them.

There are different methods that can be applied, varying with the underlying information and data. Where probabilities can be attached to different outcomes arising from an adaptation measure, economic tools such as risk and portfolio theory allow us to choose the measure that maximizes the expected net benefits allowing for the risks associated with different options. Such an approach compares not only the net benefits of each measure but also the risks associated with it (e.g. the possibility of a very poor outcome).

In some cases it is difficult to place values on some outcomes (e.g. disasters involving large scale loss of life). An alternative to the risk or portfolio theory approach can then be used, that looks for a least cost solution that keeps probable losses to an acceptable level.

In situations where probabilities cannot be defined the analyst can define scenarios that describe a possible set of outcomes for each adaptation measure. In such cases economic tools have been developed that search for solutions which meet some criteria of minimum acceptable benefits across a range of scenarios, allowing the decision-maker to explore different levels of acceptable benefits in a systematic way, providing "acceptability" can be defined. Applications in the literature can be found for sea level rise, river flooding and energy planning.

There are, however, still unanswered questions on how to apply these methods (particularly when the changes caused by climate change are non-marginal and when preferences change), and how to improve the quality of information on the possible impacts and benefits.

FAQ 17.2: Are economic approaches likely to bias adaptation policy and decisions against the interests of the poor, vulnerable and ecosystems?

An economic approach, which focuses on the costs and benefits of an action is an important component of the final decision on which action to take, given the limited resources available for addressing adaptation. A narrow economic approach can bias decisions against the poor, vulnerable and ecosystems whose value systems are often not captured, or are understated by market prices. For example, the market value of timber does not reflect the ecological and hydrological functions of trees as well as the value of non-marked non-timber forest products like medicines. But the final decision is not based on just this information. Account is also taken of who gains and who loses (the distributional effects of the action), and of the impacts of the measures on factors that are not reported in monetary terms. If one only relied on the narrow economic information, decisions could be biased against the vulnerable and against measures that are more protective of the environment and other impacts that are non-quantifiable in monetary terms. Economic data feeds into a broader decision-making framework as one of several

considerations. What is crucial is that the overall decision-framework is broad, with both economic and non-economic factors being taken into consideration.

A frequently used decision-making framework that provides for the inclusion of economic and non-economic indicators to measure the impacts of a policy or measure, including impacts on vulnerable groups and ecosystems is multi-criteria analysis (MCA). An issue that remains problematic with methods such as MCA is what weights (including equity weights) to attach to the different criteria.

Alternatively one can attach monetary values to non-market impacts, for example to changes in the services provided by ecosystems. The numbers are less certain than those attached to market impacts but they are still useful in extending the economic assessment and providing a way of comparing market and non-market impacts.

FAQ 17.3: In what ways can economic instruments be deployed to facilitate adaptation to climate change in developed and developing countries?

Economic instruments (EIs) are designed to make more efficient use of scarce resources and to ensure that risks are more effectively shared between agents in society. In the context of adaptation, EIs are useful in a number of ways. First they help to ensure that the starting point for any adaptation policy involves an efficient use of the resources that will be affected by climate change: water pricing is an example of an EI. If water is already priced properly, there will be less overuse that has to be corrected through adaptation measures when supplies become scarcer. Second, they can function as a flexible, low-cost tool for adaptation. With the same example, if climate impacts result in increasing water scarcity it is easier to adjust the water tariff and less costly than finding new ways of increasing supply.

Insurance is another economic instrument that serves as a flexible, low cost adaptation tool. Where risks can be well defined insurance markets can help reduce vulnerability and also generate funds for post disaster recovery.

Payments for environmental services (PES) schemes are evolving voluntary market based economic instruments used in countries such as Costa Rica to manage natural resources, and can be applied to adaptation. In developed countries, where markets function reasonably well, EIs can be directly deployed through market mechanisms. In many developing countries, this is not always the case and markets often need public action and support. The insurance markets for example, do not cover all risks and there are issues of affordability, which mean that public-private partnerships are often required. The public sector also has an important role in making voluntary market instruments work effectively through establishing the legal frameworks that define property rights over scarce resources such as land and water in areas where such rights are not well established. PES schemes, for example, can only function well when the public sector ensures that rights are defined and agreements honored.

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Table 17-1: Four definitions of eligible adaptation.

Relevant climatic factors Motivation for action	**Observed and/or projected climate change**	**Climate change as well as natural climate variability**
Climate is the main reason	**Definition 1:** Action occurs mainly to reduce the risks of observed or projected climate change **Example:** Raising of existing dykes	**Definition 2:** Action occurs mainly to reduce risks of climate change and climate variability **Example:** Building of new dykes in areas that are currently unprotected
Climate is one of several reasons	**Definition 3:** Actions that reduce the risks of observed or projected climate change even if they are also justified in the absence of climate change **Example:** Economic diversification in predominantly agricultural regions	**Definition 4:** Actions that reduce the risks of climate change and climate variability even if they are also justified in the absence of climate change **Example:** Improved public health services

Source: (Füssel *et al*., 2012)*, adapted from* (Hallegatte, 2008)

Table 17-2: Estimates of global costs of adaptation.

Study	**Results (billion USD/year)**	**Time frame**	**Sectors**	**Methodology and comment**
World Bank, 2006	9-41	Present	Unspecified	Cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA)
Stern, 2006	4-37	Present	Unspecified	Update of World Bank (2006)
Oxfam, 2007	>50	Present	Unspecified	WB (2006) plus extrapolation of cost estimates from national adaptation plans (NAPAs) and NGO projects.
UNDP, 2007	86-109	2015	Unspecified	WB (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC, 2007	28-67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and Financial Flows required for the international community
World Bank, 2010	70-100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Improvement upon UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea-level rise and storm surges.

Table 17-3: Coverage of adaptation costs and benefits.

Sector	**Analytical Coverage**	**Cost Estimates**	**Benefit Estimates**
Coastal Zones	Comprehensive	√√√	√√√
Agriculture	Comprehensive	-	√√√
Water	Isolated case studies	√	√
Energy	N. America, Europe	√√	√√
Infrastructure	Cross-cutting, partly covered in other sectors	√√	-
Health	Selected impacts	√	-
Tourism	Winter tourism	√	-

Source: Agrawala and Fankhauser (2008)

Table 17-4: Studies illustrating economic evaluation of adaptation options.

Sector, Study, and Scope	Methodology	Key Points Illustrated
Agriculture, Forestry, and Livestock		
Seo and coinvestigators (e.g. Seo et al , 2008, 2009, 2011): Impacts to livestock producers in Africa	Econometric. Examines the economic choices that livestock owners make to maintain production in the face of climate Insights into adaption possibilities by examining the ways economic choices vary over locations and times with varying climate conditions.	Consideration of multiple options (implicit) Residual impacts reflected Applicable at multiple geographic scales Results provide a ready means to re-estimate results for multiple climate scenarios.
Butt and McCarl (2006): Crop sector in Mali	Simulation. Simulates the economic implications of potential adaptation possibilities. Examines the consequences of migration in cropping patterns, development of heat resistant cultivars, reduction in soil productivity loss, cropland expansion, and changes in trade patterns.	Broad consideration of options (explicit, allowing for ranking of measures) Residual impacts reflected Rigorous economic costing of adaptation options and consequences for yields, revenue, and food security.
Sutton et al (2013): Crop and livestock sector in four Eastern European and Central Asian countries	Simulation with benefit-cost analysis. Ranks options initially based on net economic benefits over 2010 to 2050 period. Considers non-market and socially contingent effects through stakeholder consultation process.	Broad consideration of options (explicit, measures ranked) Very broad representation of climate scenarios (56 GCM-SRES combinations) Rigorous economic costing of adaptation options Integrated analysis of agriculture and irrigation water sectors
Sea-level Rise and Coastal Systems		
Nichols and Tol (2006):Coastal regions at a global scale	Simulation of adaptation through construction of seawalls and levees, adoption of beach nourishment to maintain recreational value, and migration of coastal dwellers from vulnerable areas. The study, reflects an economic decision-rule for most categories and benefit-cost analysis for a few categories	Capable of broad representation of sea-level rise scenarios. Optimization of alternatives considering both the impact of adaptation and resulting residual impacts. Rigorous economic costing of adaptation options.
Neumann et al. (2010a): Risks of sea-level rise for a portion of the coastal United States	Simulation of adaptation decision-making including seawalls, bulkheads, elevation of structures, beach nourishment, and strategic retreat, primarily using a benefit-cost framework but with alternatives based on local land-use decision-making rules.`	Capable of broad representation of sea-level rise scenarios Flexibility to consider both benefit-cost and rule-based decision making Rigorous and dynamic economic costing of adaptation options
Purvis et al. (2008): Risks of coastal flooding in Somerset, England	What is adaptation strategy here Simulation using a probabilistic representation to characterize uncertainty in future sea-level rise and, potentially, other factors that could affect coastal land-use planning and development investment decisions	Considers the impact of both gradual climate change (sea-level rise) and extreme events (the 1 in 200 year recurrence interval coastal flooding event). Incorporates probabilistic uncertainty analysis
Energy		
Margulis (2011): Energy production in Brazil, particularly from hydropower	Simulation of multiple adaptation options, including energy source substitution and regional "wheeling" of power coupled with modeling of river flow and hydropower production under future climatic conditions. Uses an optimization model of overall energy production	Considers multiple GHG emissions scenarios and a "no-climate change" baseline Scalable to multiple spatial resolutions, with national and regional results reported Considers multiple adaptation strategies Rigorous economic costing of capital and recurring adaptation costs
Health		
Ebi (2008): Global adaptation costs of treatment of diarrhoeal diseases, malnutrition, and malaria	What is the adaptation considered The costs of three diseases estimated in 2030 for three climate scenarios using (1) the current numbers of cases; (2) the projected relative risks of these diseases in 2030; and (3) current treatment costs. The analysis assumed that the costs of treatment would remain constant. There was limited consideration of socioeconomic development.	Multiple climate scenarios Clear description of framework and key assumptions Rigorous economic costing of adaptation options using multiple assumptions to characterize uncertainty

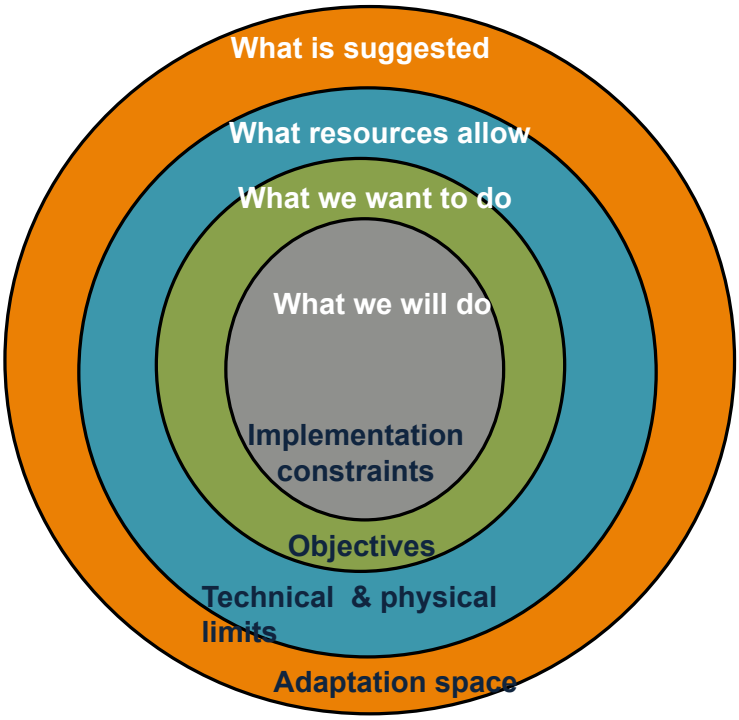

Figure 17-1: The narrowing of adaptation from suggested adaptations to what will be done. Forces causing the narrowing are listed in black.

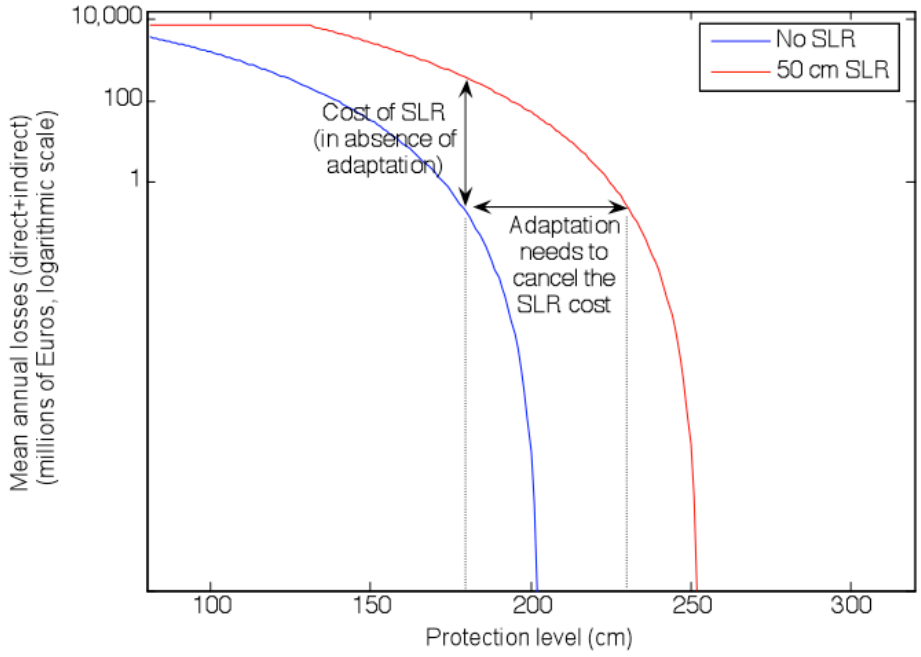

Figure 17-2. Illustrative example assuming a homogenous protection at 180 cm above current mean sea level (in the 'No SLR' and '50 cm SLR' cases). The vertical arrow shows the cost of SLR in the absence of adaptation. The horizontal arrow shows the need for adaptation to maintain unchanged mean annual losses.

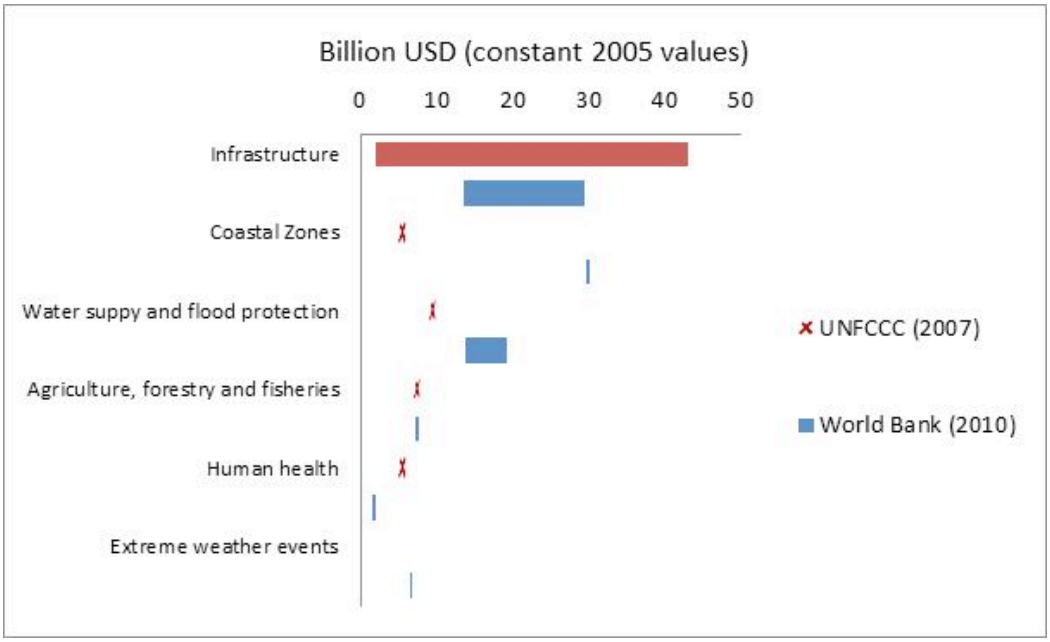

Figure 17-3: Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges, crosses point estimates.

Chapter 18. Detection and Attribution of Observed Impacts

Coordinating Lead Authors
Wolfgang Cramer (Germany), Gary Yohe (USA)

Lead Authors
Maximilian Auffhammer (USA), Christian Huggel (Switzerland), Ulf Molau (Sweden), Maria Assunção Faus da Silva Dias (Brazil), Andrew Solow (USA), Dáithí Stone (Canada / South Africa), Lourdes Tibig (Philippines)

Contributing Authors
Laurens Bouwer (Netherlands), Mark Carey (USA), Dim Coumou (Germany), Gerrit Hansen (Germany), Ove Hoegh-Guldberg (Australia), Solomon Hsiang (USA), Sari Kovats (UK), Paul Leadley (France), David Lobell (USA), Camille Parmesan (USA), Elvira Poloczanska (Australia), Hans Otto Pörtner (Germany)

Review Editors
Rik Leemans (Netherlands), Bernard Seguin (France), Neville Smith (Australia)

Volunteer Chapter Scientist
Gerrit Hansen (Germany)

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Frequently Asked Questions
18.1: What are the main challenges in detecting climate change impacts?
18.2: What is the main challenge in attributing changes in a system to climate change?
18.3: Why are detection and attribution of climate impacts important?
18.4: Is it possible to attribute a single event, like a disease outbreak or the extinction of a species, to climate change?

References

Executive Summary

Impacts of recent observed climate change on physical, biological, and human systems have been detected on all continents and in most oceans. This conclusion is strengthened by observations since the AR4 as well as through more extensive analyses of earlier observations. Most reported impacts of climate change are attributed to regional warming of the atmosphere and the ocean. The level of confidence in attribution of observed impacts to shifts in rainfall patterns is lower. There is emerging evidence of impacts of ocean acidification. [18.3-18.6]

For many natural systems, new or stronger evidence for substantial and wide-ranging impacts of climate change exists, including the cryosphere, water resources, coastal systems and ecosystems on land and in the ocean.

Cryosphere and water resources

Glaciers worldwide continue to shrink; new glacier lakes have formed and existing ones have changed; seasonal ice in many lakes and rivers forms later and breaks up earlier. A major part of these changes can be attributed with *high confidence* to climate change. [18.3.1.3, 18.5; Figure 18-3]

Widespread changes and degradation of permafrost of both high-latitude and high-elevation mountain regions have been observed over the past years and decade*s (high confidence)*. The permafrost boundary has been moving polewards and to higher elevations, and the active layer thickness has increased at many sites (*medium confidence* in attribution to climate change). [18.3.1.3, 18.5]

Hydrological systems have changed in many regions, due to changing rainfall or melting glaciers, affecting water resources, water quality, and sediment transport (*medium confidence*). In many river systems, the frequency of floods has been altered by climate change (*low to medium confidence*). The duration of droughts in some regions has been altered by climate change (*medium confidence*). [18.3.1.1, 18.5]

Terrestrial and freshwater ecosystems

Across all climate zones and continents, an increasing range of species and communities in terrestrial ecosystems have been impacted by recent climate change and increasing atmospheric CO_2. Many plants and animals show changes in phenology (*high confidence*), productivity and / or geographic range (*medium confidence*). Elevated rates of extinction cannot be attributed to climate change. [18.3.2, 18.5]

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in animal community composition, especially in headwater streams. While confidence in detection of change is *high*, there is *low confidence* in attribution to climate change due to many confounding factors. [18.3.2.4, 18.5]

Several major terrestrial ecosystems are undergoing broad-scale changes that can be characterized as early warnings for coming regime shifts, in part due to climate change. For wide-spread shrub encroachment in the Arctic tundra there is *high confidence*, for boreal forest tree mortality there is *low confidence* of climate change as driver. The recession and degradation of the Amazon forest cannot be attributed to climate change. [18.3.2.4, 18.5.6, 18.5.7]

Oceans and coastal systems

The physical and chemical properties of the ocean have changed significantly over the past 60 years, due to anthropogenic climate change. **As a result, marine organisms have moved to higher latitudes,**

changed their depth distribution or their phenology (*high confidence*). Facilitated by changes in the distribution of sea ice and changes in ocean currents, organisms such as crustaceans, zooplankton and fish have migrated toward higher latitudes. These changes also affect coastal ecosystems including kelp forests and seagrass meadows [18.3.3, 18.3.4.1]

Climate change has influenced ocean primary productivity, with positive consequences for some fisheries and negative ones for others (*medium confidence*). Together with non-climate influences such as excess nutrient input from human activities, climate change has contributed to an increase in the frequency, geographical distribution, and severity of hypoxic areas in the ocean. [18.3.4.1, 18.3.4.2]

Due to the increased frequency of stress events arising from elevated sea temperatures, coral reefs have experienced increased mass bleaching and mortality (*very high confidence*). These events have contributed to the loss of reef building corals in many parts of the world since the early 1980s. [18.3.3, 18.3.4, Box 18-3, 18.5, Table 18-8, Box CC-CR]

Arctic sea ice has been shrinking in extent, thickness, composition, with observed impacts on marine biology and the livelihoods of indigenous people (*medium to high confidence*). [18.3.1.3, 18.3.4, 18.4.7, 18.5.7]

Despite the known sensitivity of coastal systems to sea-level rise, local perturbations from regional variability in the ocean and human activities preclude the confident detection of sea level-related impacts attributable to climate change outside of the Arctic. [18.3.3]

For managed ecosystems and human systems, the effects of changing social and economic factors often dominate over any direct impact of climate change. Despite this, numerous impacts of climate change have been detected.

Even accounting for changes in technology and other non-climate factors, agricultural crop yields have changed in many regions in response to climate. Yields have increased in some (mid to high latitude) regions, due to warming and higher CO_2 *(low confidence)*, and decreased in other (mainly low latitude) regions due to water shortages and higher temperatures *(medium confidence*). Despite the high sensitivity of crop yields to temperature extremes, observed trends in the agricultural markets cannot presently be attributed to climate change, due presence of other drivers. [18.4.1, Table 18-9]

The catch potential of fisheries has increased in some regions and decreased in others with consequences for the food and livelihood of involved human communities (*high confidence*). Fisheries at high latitudes are showing increased productivity due to sea ice retreats and increases in net primary productivity. In other regions, stratification of the water column driven by warming has reduced net primary productivity of the ocean. [18.3.4, 18.4.1.2, 18.5.7]

In some regions, increases in the prevalence of vector-borne diseases have been detected and attributed to warming. Dengue fever and malaria have increased in several regions of the world over the past few decades, but there is *very low confidence* in attribution of these trends to climate change. [18.4.5]

Climate impacts on Arctic indigenous groups have been detected and attributed to climate change. These include changes in seasonal migration and hunting patterns, health, and cultural identity (*medium confidence*). [18.4.7, Box 18-5, 18.5.7, Table 18-9]

Extreme climate events have impacted natural and physical livelihood assets, incomes, public health, and social institutions. Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, but with a documented contribution of climate change and variability in some cases. [18.4.4, 18.4.7]

Despite known vulnerabilities and increasing exposure to climatic stressors, impacts of climate change on human livelihoods have rarely been detected with confidence. Such detection is complicated by the effects of other economic and social factors. There is emerging literature on the impact of climate on poverty, working conditions, violent conflict, migration, and economic growth, but evidence for detection or attribution remains limited. [18.4.3, 18.4.6, 18.4.7]

Detection and attribution of observed impacts of climate change supports assessments of current conditions with respect to "Reasons for Concern" formulated by earlier IPCC assessments. The degree to which projected damages are now manifest, or the detection of stronger early warning signals for expected impacts, can contribute to a more comprehensive risk assessment for dangerous anthropogenic interference with the climate system.

Increases in "risks to unique and threatened systems" are now documented with higher confidence by the observed impacts on Arctic marine and terrestrial ecosystems and indigenous livelihoods (*medium to high confidence*), tropical coral reefs (*high confidence*) and glaciers in most mountain regions (*high confidence*). Observed impacts thus confirm this reason for concern. [18.6.2.1]

"Risks of extreme weather events" – extreme warming events continue to increase for warm water coral reefs (*high confidence*), confirming this reason for climate-related concern. Risks have also increased in some other systems, causing economic losses, however this is predominantly due to the increases in wealth and exposure. [18.6.2.2]

Impacts of climate change have now been documented globally, covering all continents and the ocean (*high confidence*). However, research coverage is still insufficient and too heterogeneous to effectively address spatial or social disparities concerning the "distribution of impacts" beyond local case studies. [18.6.2.3]

"Aggregate impacts" have been documented with measures of glacier volume and permafrost extent (*medium to high confidence*). There is limited evidence of a climate contribution to aggregate impacts on biospheric carbon fluxes, agricultural yields, fishery production and economic losses due to extreme weather, due to the presence of dominant non-climatic drivers. For the cryospheric impacts, observations clearly confirm the reason for concern. [18.6.2.4]

"Risks from large-scale singularities" relating to irreversible shifts with significant feedback potential in the Earth system have yet to be observed. However, there is now robust evidence of significant early warning signals in observed impacts of climate change that indicate large-scale regime shifts for the Arctic region and the tropical coral reef systems. This evidence confirms reasons for concern. [18.6.2.5]

Though evidence is improving, there is a persistent gap of knowledge regarding how large parts of the world are being affected by observed climate change. The number of attribution studies linking observed impacts to the anthropogenic component of climate change remains limited. Research to improve the timeliness and knowledge about the detection and attribution is needed in particular for the risk of extreme events. [18.7]

In most studies, the attribution of observed impacts and vulnerabilities is related to all changes in climate that represent deviations from historical means and / or historic variability. Only a smaller number of robust attribution studies link responses in physical and biological systems to *anthropogenic* climate change. [18.1]

Methods for rigorous assessment of observed impacts of climate change are evolving. Evidence for attribution comes from assessment of the relative contribution by all known drivers affecting the dynamics of a system to its behavior, using scientific methods, involving an assessment of confidence in both detection and attribution. Formal meta-analysis or aggregated assessments of many observations or studies can help to improve confidence. [18.2.1, Box 18-1]

18.1. Introduction

This chapter synthesizes the scientific literature on the detection and attribution of observed changes in physical, biological and human systems in response to the climate change that has occurred during the recent few decades. It assesses the degree to which detected changes in such systems can be attributed to observed climate change and where possible, separates out the relative importance of anthropogenic drivers of climate change. For most natural and essentially all human systems, climate is only one of many drivers that cause systems to change, which therefore requires a careful accounting of the importance of other confounding factors on the overall change in these systems.

18.1.1. Scope and Goals of the Chapter

Previous assessments, notably Rosenzweig *et al*. (2007), in the IPCC Fourth Assessment Report (AR4), and the increasing body of literature published since, indicated that numerous physical and biological systems are affected by recent climate change. Human systems have received comparatively little attention in this literature, with the exception of the food system, which is a coupled human/natural system. Rigorous formal assessment of the literature going beyond just detection of change across a variety of regions and sectors, to scientifically robust attribution to climate change and its anthropogenic drivers is critical for several purposes (Brander *et al*., 2011; Hoegh-Guldberg, 2011; Stocker *et al*., 2011). Only formal detection studies provide robust evidence of where climate change impacts already being observed and where they are not, supporting near-term planned adaptation if and where necessary.

For policy makers and the public, detection and attribution of observed impacts will be a key element to determine the necessity and degree of mitigation and adaptation efforts. Detection and attribution are vital parts of the evidence base requested of the IPCC by signatories to the United Nations Framework Convention on Climate change to judge policies aiming to stabilize “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous atmospheric interference with the climate system”.

Full attribution of changes in these systems to anthropogenic climate is extremely hard to accomplish for many complex systems with diverse responses and multiple significant confounding drivers (Parmesan *et al*., 2011). There has, however, been a significant increase in studies attributing changes in some systems to local climate change without direct linkage to anthropogenic drivers. This chapter assesses the studies that exist for both full and partial attribution, and the methodologies that can be brought to bear on attribution and the uncertainties inherent in doing so.

18.1.2. Summary of Findings from the AR4

Rosenzweig *et al*. (2007) reported that “observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases.” In particular, they highlighted several areas where this general conclusion could be supported by specific conclusions that were reported with *high confidence:*

- Changes in snow, ice and frozen ground had been seen to increase ground instability in mountain and other permafrost regions; these changes had led to changes in some Arctic and Antarctic ecosystems and produced increases in the number and size of glacial lakes.
- Some hydrological systems had been affected by increased runoff and earlier spring peak discharges; in particular many glacier- and snow-fed rivers and lakes had warmed, producing changes in their thermal structures and water quality.
- Spring events had appeared earlier in the year so that some terrestrial ecosystems had moved poleward and upward; these shifts in plant and animal ranges were attributed to recent warming.
- Shifts in ranges and changes in algal, plankton and fish abundance as well as changes in ice cover, salinity, oxygen levels and circulation had been associated with rising water temperatures in some marine and freshwater systems.

In terms of a global synthesis, this assessment noted "that it is likely that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems" (Rosenzweig *et al*., 2007). Though it was based on analyses of a very large number of observational datasets, the assessment noted a lack of geographic balance in data and literature on observed changes, with marked scarcity in low and middle income countries.

Observed impacts to human systems were less obviously attributed to anthropogenic climate change. Rosenzweig *et al*. (2007) concluded with *medium confidence* only that, "other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers". They especially noted effects of temperature increases on:

- Some agricultural and forestry management practices in the higher latitudes of the Northern Hemisphere; these included earlier spring planting as well as changes in the disturbance regimes of fires and pests.
- Some aspects of human health, including heat-related mortality in Europe, changes in some vectors of infectious diseases across the world, and phenological changes in allergenic pollen in the mid to high latitudes of the Northern Hemisphere.
- Some human activities in the Arctic (such as hunting and travel) and in lower-elevation alpine areas (such as mountain sports).

18.2. Methodological Concepts for Detection and Attribution of Impacts of Climate Change

There are three substantial challenges to the detection and attribution of change in environmental systems to a changing climate. First, all systems are affected also by environmental factors other than climate; to detect a climate change impact, it is therefore necessary to control for the effects of such confounding factors. Second, the ability of many systems to adapt to change complicates the detection and attribution of any impacts; that is, adaptation can mask an impact. Detection (and attribution) of adaptation to climate change is in this chapter considered to be detection (and attribution) of a climate change impact (Box 18-1). Third, because systems are typically affected by local or regional climate change, attribution of a detected climate change impact to anthropogenic climate change can be difficult. To overcome these difficulties and to best account for all available knowledge on observed impacts, a range of methods is employed here. They are summarized in this section.

18.2.1 Concepts and Approaches

18.2.1.1. Detecting and Attributing Change in the Earth System

From an analysis perspective, the Earth system can be separated into three connected subsystems; we name them here as the climate system, the natural system, and the human system (Figure 18-1). Many external drivers may influence any system, including the changing climate and other confounding factors (Hegerl *et al*., 2010). Each climate, natural or human subsystem affects the other two directly or indirectly. For example, the human system may directly affect the natural system through deforestation, which in turn affects the climate system through changes in albedo; this can alter surface temperatures which in turn feed back on natural and human systems.

[INSERT FIGURE 18-1 HERE
Figure 18-1: Schematic of the subject covered in this chapter. The Earth system can be divided into three broad interacting systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone *et al*. (2013).]

If an observed change in the human system impacts the climate system, we call this an anthropogenic driver of climate change. In order to highlight potential reasons for concern (including the uncertainties in detection and

attribution), impacts of any observed climate change are covered in this chapter, irrespective of whether the particular aspect of climate change has been identified as anthropogenic.

18.2.1.2. Concepts of Detection and Attribution of Climate Change Impacts

Concepts and approaches to detection and attribution have been evolving throughout the work of the IPCC. In 2010, an IPCC Expert Meeting on Detection and Attribution was held to reconcile methods and terminology across IPCC working groups. The report from this meeting (Hegerl *et al*., 2010), along with the discussion of Stone *et al*. (2013), is an important conceptual basis for this chapter.

Detection *addresses the question of whether a system is changing beyond what might be considered normal behaviour in the absence of climate change*. While Hegerl *et al*. (2010) proposed a broad definition that could be used across IPCC Working Groups, this definition, used in this chapter and in other Working Group II chapters, is more specific in not just considering any observed changes (Stone *et al*., 2013). The appropriate reference normal behaviour may be stationary (e.g. glaciers) or non-stationary (e.g. economic activity), and the nature of that reference needs to be spelled out clearly. Typically, detection studies involve the initial assumption of climate being at least one of the drivers of that change, but other drivers (such as changes in land use) may be recognized to play a significant role too. For many systems, the role of these confounding factors may exceed that of climate change.

Attribution *addresses the question of whether climate change has contributed substantially to the detected change in a system*. In practice, attribution studies ask how much of the observed change is due to climate change. Attribution requires the evaluation of the contributions of all external drivers to the system change.

Failure to include relevant factors in an attribution study can lead to erroneous conclusions. This is referred to as the omitted variable problem (Greene, 2003). It is a particular problem in time series regressions when both climate and non-climate factors may vary roughly monotonically over time. It is also important not to equate empirical correlation with causality (Holland, 1986). This underscores the crucial role that system understanding must play in high-quality detection and attribution studies.

Detection and attribution studies rely on quantitative or qualitative analysis. Quantitative studies adhere to basic principles of statistical inference. One is that effects of formal or informal variable selection – in which a range of statistical models is screened to identify the best-fitting model – must be taken into account to avoid spurious attribution (Chatfield, 1995).

Qualitative attribution studies typically involve the identification of multiple, intersecting “impact chains” that recognize confounding variables acting alongside climate change. These studies usually do not specifically isolate certain social or environmental changes to climate change alone but rather, they aim to identify dynamic interactions among an assemblage of intersecting forces in human-environment systems.

Evidence for testing the hypothesis that some observed change can be attributed to climate change may come from different sources. The nature of the tools used for testing hypotheses varies depending on the details of the study (Stone *et al*., 2013). Mechanistic models can be used, for example representing a system through a chain of explicit functions based on understanding of the individual processes that together comprise the mechanics of the system. These mechanistic models can sometimes be formulated numerically. In other cases, empirical models may be useful, relating the response of a system to external drivers according to mathematical relationships estimated through observation, experimentation, or survey. In practice, though, many modeling setups will contain both mechanistic and empirical components.

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Box 18-1. The Role of Climate Sensitivity and Adaptation for Impact Models in Human Systems

Impacts of climate change on a measurable attribute of a human system only occur if a) the attribute is sensitive to climate and b) a change in climate has occurred. A large literature has developed attempting to quantify both climate sensitivity of various systems and observed changes in climate.

The literature estimating the climate sensitivity of an outcome such as crop yields, heat related mortality or migration, has relied on observed climate variability either across space (e.g., Schlenker *et al*., 2005), time (e.g., Mann and Emanuel, 2012), or space and time (Hsiang *et al*., 2011; e.g., Dell *et al*., 2012). While there is a rich literature using climate variability across space, the long observational weather time series required for exploring climate variability across space and time have limited the opportunities for study. A number of studies have instead estimated the weather sensitivity of outcomes in order to project the future impacts of weather under climate change (Deschênes and Greenstone, 2007; Deschênes and Greenstone, 2011), or attribute impacts for the past (Auffhammer *et al*., 2006). The issue with impact studies using a weather based sensitivity measure is that they cannot provide estimates of impacts based on the climate sensitivity. For example, farmers may respond to an unusually hot summer, which is a weather event, by applying more irrigation water. However, in the long run farmers may respond to a warmer climate by switching crops, changing irrigation technology or abandoning farming altogether. The two sensitivities and resulting magnitudes of attributable impacts due to a change in weather versus a change in climate are therefore different.

In order to detect and attribute a change in a system to climate change, one needs to combine a measure of sensitivity of the outcome to climate with an observed measure of climate under climate change. This can be done via a multi-step approach (Hegerl *et al*., 2010), whereby one estimates the outcome of interest using measures of climate sensitivity combined with measures of observed climate and compares these to a simulated outcome using the same sensitivity but removing the climate change from the climate input.

_____ END BOX 18-1 HERE _____

18.2.1.3. Approaches to Attribution

There are many levels at which drivers and responses can be defined for observed impacts of climate change (Table 18-1). In practice, two different levels of external drivers are used:

- Attribution to climate change, where impacts are related to identified long-term trends in climate (including changes in variability patterns). Studies examining this relationship do not formally identify the role of anthropogenic emissions in the observed climate change or, by extension, in the observed impact, but they do indicate the degree to which the system is sensitive to long term climate change.
- Attribution to anthropogenic climate change, where impacts are related, via the climate, to anthropogenic emissions of greenhouse gases and other human activities that are affecting the climate. Because of the complexity of the causal chain, investigation of this relationship is extremely challenging (Parmesan *et al*., 2011) and only a limited number of these studies have been performed to date.

Attribution studies use two main approaches (see Figure 18-2). Single-step methods consider all relevant systems in a single setup. The assessment tool can comprise a single model or a sequence of models, provided the output of each model is directly employed as an input for the next model in a logical sequence. The attribution analysis is performed through a comparison of the change in the final output from the model(s) against the observed change in the system of interest.

[INSERT FIGURE 18-2 HERE
Figure 18-2: A schematic diagram comparing approaches to attribution for an ecological system. The multi-step approach differs from the single-step approach in having a discontinuity between the attributed climate change and the observed weather driving the ecological model. Adapted from Stone *et al*. (2013).]

Multi-step attribution approaches comprise multiple attribution analyses, with an overall conclusion deduced from the collection of analyses. A multi-step approach could include an analysis of the attribution of changes in a measure of interest to changing climatic conditions and a separate analysis of how external climate drivers affected relevant climatic conditions. Typically, the separation of these analyses creates gaps or inconsistencies between the outputs from one step and the inputs to the next. These gaps must be assessed themselves with respect to their impact on the confidence in the overall attribution.

In areas where extensive monitoring records are available, such as for phenological measures in ecological systems, studies may be combined into a formal quantitative synthesis assessment. For instance, Rosenzweig *et al.* (2008) noted that the spatial pattern of observed changes in a large number of natural systems around the globe matched the pattern expected based on the observed warming pattern, and argued that other global factors such as land use change could not account for this pattern (see also Box 18-2).

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Box 18-2. Quantitative Synthesis Assessment of Detection and Attribution Studies

There are a number of powerful tools for quantitative synthesis assessment of detection and attribution across multiple studies. These tools include associative pattern analyses (e.g., Rosenzweig *et al.*, 2008) and regression analyses (Chen *et al.*, 2011) which compare expected changes due to anthropogenic climate change across multiple studies against observed changes.

Quantitative synthesis assessments have been particularly prominent in ecology, where measures of phenology (timing of seasonal events) and geographical range can be assembled across species into standardized indices (Parmesan and Yohe, 2003; Rosenzweig *et al.*, 2008; Chen *et al.*, 2011). Synthesizing across multiple species can increase our confidence in detection of general patterns of change in the biological indices. This confidence increases with the number of species / ecosystems observed, the number of independent studies, the geographical distribution of these observations, the temporal depth and resolution of the data, and the representativeness of species/ecosystems and locations studied.

Synthesis assessments examining climate change as the only driver can provide some insight into the attribution of biological responses to climate change because they can indicate whether plausible hypotheses are supported by data. However, increasing spatial coverage, numbers of species, etc. does not a priori increase confidence that climate change is a more credible explanation for biological change than alternative hypotheses. Additional data can contribute to confidence in causal relationships, i.e. attribution, in a synthesis assessment when it provides new evidence for explicit testing against a credible range of alternative hypotheses.

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18.2.2. Challenges to Detection and Attribution

18.2.2.1. Types and Quality of Observations

The nature of indicators can take many forms, some of which are more amenable for precise long-term monitoring than others. Many changing phenomena can be measured directly, e.g., the temperature of the surface waters of a lake. Often, however, important indicators are less specific and thus difficult to pinpoint, for instance the excess mortality and increased human vulnerability associated with heat waves, or the percentage of species migrating polewards or upwards.

The quality of observations of these indicators varies in space and time. Monitoring of ecosystems, for example, is often not designed with the intention of measuring incremental long-term changes and are not optimized for the detection of climate-related changes (Midgley *et al.*, 2007). Consequently, the record length may be too short, too

heterogeneous or discontinuous to be useful, or measuring standards may have been improved through time resulting in measurement artifacts. This latter factor is most visible in the extensive and long-running networks designed to monitor human health, where the priority is an accurate timely assessment of current health status and risk rather than the determination of long-term trends (see also 18.4.5).

18.2.2.2. Spatial and Temporal Characteristics of Change

Detection studies require observational data spanning a time period longer than the typical time scale of natural variability in the system in the absence of external drivers. A particular challenge is that this required time scale is usually difficult to discern from available observational records and thus other sources of information must be used to determine them (Hegerl *et al.*, 2010). Lags between changes in external drivers and responses to those drivers vary among different impact systems and within them, from seconds or minutes to centuries or millennia, and thus need to be recognised (Stone *et al.*, 2013).

Non-linear system response to change is a fundamental issue for detection studies. Some systems may respond by step-wise changes, other systems may have tipping points, showing little or no change until a certain threshold where they suddenly start to respond vigorously and often in a chaotic way (e.g., De Young and Jarre, 2009; Wassmann and Lenton, 2012, 18.6.2.5).

Change in environmental and human systems occurs on multiple spatial scales from local to global. Attribution of change to climate change (e.g., over the last several decades) faces different challenges at different spatial scales. At the local scale, detection may be straightforward due to the availability of long-term observations, but attribution may be difficult because many local factors have been changing as well (e.g., Parmesan *et al.*, 2013). Furthermore, local climate may be affected by localised drivers such as land cover change (De Noblet-Ducoudré *et al.*, 2012), which complicates the evaluation of the role of global anthropogenic emissions.

18.2.2.3. Publication Bias

Conclusions about the effect of climate change on natural and human systems in this report are based on a synthesis of findings in the scientific literature. A potential problem with this approach is publication bias, specifically the preferential publication of papers reporting statistically significant findings (Parmesan and Yohe, 2003). The effect of publication bias could be a false impression of the strength of the evidence in favor of a hypothesized effect. Methods exist for detecting and correcting for publication bias in formal quantitative synthesis analysis (Rothstein *et al.*, 2005). For instance, the availability of a large sample of observations from an existing phenological monitoring network has permitted the assessment that publication bias has not been an important factor in conclusions about the role of climate change in studies of the timing of leafing, flowering, and fruiting in Europe (Menzel *et al.*, 2006), but the lack of such long-term monitoring networks preclude such a conclusion for measures related to vector-borne diseases (Kovats *et al.*, 2001).

18.3. Detection and Attribution of Observed Climate Change Impacts in Natural Systems

The IPCC AR4 provided extensive reporting on observed impacts of climate change (in Rosenzweig *et al.*, 2007, but also other chapters of the WGII report). The scientific literature on this topic is growing quickly. Rather than a full analysis of this literature, the following section provides a synthetic overview of the state of knowledge across major sectors of natural systems, based largely on the respective sectoral chapters (3, 4, 5, 6) and chapter 30 of this report, and a methodological framework with these chapters.

18.3.1 Freshwater Resources

The availability of freshwater resources, and essentially all aspects of the hydrological cycle, are affected by climate change on all continents and probably most islands, with different characteristics of change in different regions. Observed changes in each of the components of the water system are assessed by the IPCC WGI in their chapters 2 and 10, and WGII in their chapters 3, 4 and the regional chapters.

Figure 18-3 presents a synthesis of confidence in detection of changes in freshwater resources and related systems (notably erosion and slope stability), and their attribution to climate change. Frozen components of freshwater systems tend to show higher confidence in detection and attribution, while components that are strongly influenced by non-climatic drivers, such as groundwater or river flow, have lower confidence.

[INSERT FIGURE 18-3 HERE
Figure 18-3: Levels of confidence in detection and attribution of observed climate change impacts for freshwater systems over the past several decades, based on expert assessment contained in this section 18.3.1 and augmented by subsections of chapter 3 as indicated. Numbered symbols refer to: Freshwater systems (18.3.1.1): 1 groundwater depletion (Ch.3.2.4), 2 changing river flow (Ch. 3.2.3), 3 changing flood frequency or intensity (Ch. 3.2.3), 4 reduction in lake and river ice duration or thickness (Ch. 18.3.1.2); Cryosphere: 5 shrinking glaciers (Ch. 3.2.2; 18.3.1.2), 6 changes in glacier lakes (Ch. 18.3.1.1), 7 erosion and degradation of arctic coastal permafrost (Ch. 18.3.1.2), 8 degradation and thaw of lowland and mountain permafrost (Ch. 18.3.1.2), Soils and rock (18.3.1.3): 9 increasing erosion (Ch.3.2.6), 10 changes in shallow landslides (Ch.3.2.6), 11 increasing frequency of alpine rock failures.]

18.3.1.1. The Regional Water Balance

The regional water balance is the net result of gains (precipitation, ice and snow melt, river and groundwater inflow) and losses (evapotranspiration, water use and river and groundwater outflow). Impacts of climate change include reduced availability of freshwater for use (one of the variables defining drought) or excess water (floods). Evapotranspiration, being a function of surface temperature, vegetation cover, soil moisture and wind, is affected by the changing climate, but also by changing vegetation processes and land cover.

At the global scale, human influence has contributed to large scale changes in precipitation patterns over land and, since the mid 20th century, in extreme precipitation (medium confidence, WGI AR5 Chapter10, Min *et al.*, 2011). More locations worldwide have experienced an increase than a decrease in heavy rainfall events, yet with significant regional and seasonal variations (Seneviratne *et al.*, 2012). While runoff has not changed in the majority of rivers, year-to-year variability has increased (WGI AR5 Chapter 2). At the regional scale, however, human influence has affected streamflow and also evapotranspiration (WGI AR5 Chapter 10).

Change in river flow is a direct indicator of a changing regional water balance. Globally, one-third of the top 200 rivers (ranked by river flow) show statistically significant trends during 1948–2004, with the rivers having downward trends (45) outnumbering those with upward trends (19) (Dai *et al.*, 2009). In the western United States, observed changes in the hydrological cycle (river flow, snow pack) during the second half of the 20th century have been linked to recent climate change, and 60% thereof were due to anthropogenic influences (Barnett *et al.*, 2008). Likewise, the Uruguay River in South America experienced a positive trend in average streamflow from 1960 to 2000, due to increased rainfall, with shorter-term peaks in runoff caused by changes in land cover (Saurral *et al.*, 2008). In the Yellow River in China, however, long-term change in streamflow are mostly attributed to anthropogenically enhanced soil erosion rather than to climatic changes (Zhang *et al.*, 2007). Changes in rainfall seasonality in monsoon systems also affect river flows. In South America, for example, wet seasons have increased in duration from an average of 170 days before 1972, to 195 days after (Carvalho *et al.*, 2010), with significant impacts on the Amazon and the La Plata basins.

18.3.1.2. Floods and Droughts

Floods, defined as impacts caused by the overtopping of river banks and levées, have increased in magnitude and frequency over recent decades in many river systems. There are limited instrumental records for these, and the existing gauging stations do not necessarily report whether impact-relevant overtopping has occurred. In addition, the highest annual flood will not necessarily imply the same overtopping each year. Other confounding factors, such as human alteration of river channels and land use also play a role, hence there is only *low to medium confidence* in global detection of a change in floods.

In regions with detected increase in heavy rainfall events and supposable consequences for pluvial floods (North America, Central Europe), both increases and decreases in floods have been found (Petrow and Merz, 2009; Villarini *et al.*, 2009). An attribution study using a multi-step modeling framework of floods suggests that an anthropogenic signal is detectable for a 20% increase in flood risk for the autumn 2000 floods in England and Wales (Kay *et al.*, 2011; Pall *et al.*, 2011, see also 18.4.4.2).

In mountain areas, glacial lake outburst floods (GLOFs) are characterized by their low frequency and high magnitude with most devastating impacts on downstream areas. While there is no evidence for a change in frequency or magnitude of GLOFs anywhere in the world (Seneviratne *et al.*, 2012), changes in the number and area of glacial lakes have been observed, with varying degrees of increasing trends in several regions over the Hindu Kush Himalayan mountain arc in the past two decades (Gardelle *et al.*, 2011), and a similarly strong increase in lake numbers in the Andes of Peru in the second half of the 20th century (Carey, 2005), and in northern Patagonia from 1945 to 2011 (Loriaux and Casassa, 2013). The growing number of these lakes is of concern since it suggests an increased likelihood of GLOFs.

Since the 1950s some regions of the world have experienced more intense and longer droughts (*medium confidence*), although a global trend cannot currently be established (Seneviratne *et al.*, 2012). Drought conditions have increased (with *medium confidence*) in Southern Europe and the Mediterranean, West Africa, East Asia, Southern Australia and New Zealand, and decreased in most of North America and Northern Australia (the rest of the world had either no change or insufficient data).

Groundwater storage has been reduced in large parts of the world, and this has been primarily attributed to human activities, such as in northeastern India where groundwater depletion, as detected by satellite data for the 21st century, was largely attributed to groundwater withdrawal for irrigation and other human use (Rodell *et al.*, 2009). Attribution of groundwater change to climatic drivers is more rare (Taylor *et al.*, 2012). For Kashmir (India), Jeelani (2008) suggests that the observed decline in groundwater recharge between 1981 and 2005 can be attributed to decreasing precipitation and glacier retreat, while a modeling study for southeast Spain indicates an effect of temperature related changes in evapotranspiration on groundwater (Aguilera and Murillo, 2009).

Water quality in watersheds and lakes is expected to change with increasing temperature through an increase in eutrophication. It is difficult, however, to link observed changes in water quality to climate change due to the counfounding factors. Eutrophication is mostly driven by other causes, such as untreated sewage inflows in urban and industrial areas and surface runoff delivering residues of fertilizers used in agriculture, and vegetation decay and manure inputs in flooding events (Kundzewicz and Krysanova, 2010). There is emerging evidence for downstream impacts on water quality due to upstream climate impacts, such as high sulfide content in rivers of Peru's Cordillera Blanca due to sulfide-rich rocks that became exposed as glaciers retreated (Fortner *et al.*, 2011).

18.3.1.3. The Cryosphere

There is extensive evidence of significant recent changes in various componentes of the cryosphere, including glaciers, ice sheets and floating ice shelves, sea, lake and river ice, subsurface ice (permafrost) and snow (WGI AR5 Chapter 4). It is *likely* that there is an anthropogenic component in the changes observed in Arctic sea ice, Greenland surface melt, glaciers, permafrost and snow cover (WGI AR5 Chapter 10).

Changes in glaciers continue to provide a globally largely homogeneous but regionally variable signal of retreat. There is *high confidence* that glacier changes over the past 2-3 decades exceed internal variability, but only few studies are available that attribute these glacier changes to anthropogenic forcing (WGI AR5 Chapter 10). The absolute contribution of glaciers and ice caps to sea level rise has increased since the early 20th century and has been close to 1 mm yr^{-1} for the past two decades (WGI AR5 Chapter 4), around a third of total observed sea level rise. The decadal-scale mass loss of ice sheets and glaciers causes accelerated uplift of underlying land in the North Atlantic Region (Jiang *et al*., 2010). There is *medium confidence* regarding the effects of decadal ice loss on seismicity due to unloading of the lithosphere beneath ice sheets (Hampel *et al*., 2010) and Alaskan glaciers (Sauber and Ruppert, 2008), and on volcanic activity such as enhanced magma generation (Sigmundsson *et al*., 2010). The strong and rapid downwasting observed on alpine glaciers has prompted a number of impacts. Expanding or new lakes at the margin of many retreating glaciers in the Alps of Europe, Himalayas, Andes and other mountain regions have altered the risk of outburst floods. In the Swiss Alps and the Peruvian Andes, outburst floods from several lakes in the 21st century have caused damages, and required risk reduction measures on the order of tens of millions USD (Huggel *et al*., 2011; Carey *et al*., 2012b). New glacier lakes have also become a tourist attraction, led to additional infrastructure, and stimulated assessment of potential for hydropower generation (Terrier *et al*., 2011). There is also evidence of slope instabilities as a consequence of recent decadal scale glacier downwasting (Haeberli and Hohmann, 2008; Huggel *et al*., 2011).

Depending on local conditions, variations in runoff in high-mountain regions are often attributed to glacier and climate change (Casassa *et al*., 2009). Current understanding suggests that during the continuous shrinkage of glaciers a 'peak meltwater' exists, with increasing runoff trends before, and decreasing trend after this threshold (3.4.4). An increase in runoff from glacier areas has been documented for catchments in western and south-central China over the past several decades, and for western Canada and Europe (Zhang *et al*., 2008; Moore *et al*., 2009; Li *et al*., 2010; Stahl *et al*., 2010). In the Peruvian Andes there is evidence that 'peak meltwater' has recently been passed, based on runoff decrease during the dry season in seven out of nine glacier-fed catchments in the Cordillera Blanca (Baraer *et al*., 2012), also confirmed by qualitative observations made by local people (Bury *et al*., 2010; Carey *et al*., 2012a). In the Swiss Alps, positive variations in river runoff have occurred primarily in highly glaciated catchments during warm periods of the 20th century (1940's, 1990's), while for less glaciated catchments a runoff decrease was detected for the warm and dry 1990s (Collins, 2006; Pellicciotti *et al*., 2010). For large catchments (Po and Rhône catchments with <1% basin glacier cover), the contribution of glacier melt to total runoff in August was significantly lower for 2004-2008 than for the previous twenty years (Huss, 2011).

Earlier reported trends of Arctic sea ice decline in terms of extent and thickness have continued, with a significant increase of the rate of sea ice decline in the first decade of the 21st century (WGI AR5 Chapter 4). It is *likely* that at least some of the decline in Arctic sea ice extent can be attributed to anthropogenic climate forcing (WGI AR5 Chapter 10). Observations by Inuit people in the Canadian Arctic confirm with *high confidence* the instrumental observations on the various changes of sea ice (see Box 18-5). Antarctic sea ice has slightly increased over the past 30 years, yet with strong regional differences (WGI AR5 Chapter 4).

For lake and river ice, there is generally *high confidence* of later freeze-up and earlier break-up over the past 100+ years, yet with regional differences (WGI AR5 Chapter 4). Changes in lake and river ice can have effects on freshwater ecosystems, transport and traffic over frozen lakes and rivers, and ice induced floods during freeze-up and break-up events (Voigt *et al*., 2011). Some evidence exists in Europe that ice-jam floods were reduced during the last century due to reduced freshwater freezing (Svensson *et al*., 2006).

Combined in-situ and satellite observations indicate a decline in snow cover extent in most months of the period 1922-2010, with the largest decline in spring (8%) (WGI AR5 Chapter 4). Only few formal detection and attribution studies exist but they consistently indicate an anthropogenic influence on snow cover reduction (WGI AR5 Chapter 10), including an up to 60% contribution of anthropogenic climate forcing on changes in snow pack and runoff timing between 1950 and 1999 in the Western United States (Barnett *et al*., 2008). Impacts on winter tourism have been observed (18.4.3.3).

Widespread changes and degradation of permafrost of both, high-latitude/low-land and high-elevation mountain regions, have been observed over the past years and decades (WGI AR5 Chapter 4). Generally, the permafrost

boundary has been moving polewards and to higher elevations, and the active layer thickness has increased at many sites. While formal attribution studies are hardly available for any of the above mentioned permafrost attributes, several impacts have been related to permafrost changes, including an increase of flow speed of Alpine rock glaciers in particular in the 21st century, resulting in rock fall and debris flows (Kääb *et al.*, 2007; Delaloye *et al.*, 2010), expansion and deepening of thermokarst lakes, erosion at the Arctic coast, resulting in a doubling of the erosion rate at Alaska's northern coastline over the past 50 years (Karl *et al.*, 2009). Furthermore, expansion of channel networks (Toniolo *et al.*, 2009), increased river bank erosion (Costard *et al.*, 2007) and higher dynamics in shrinkage and expansion of lakes and ponds have been observed in the Arctic (Rowland *et al.*, 2010), as well as an increase in hillslope erosion and landsliding in Northern Alaska since the 1980's (Gooseff *et al.*, 2009). Complex feedbacks and interactions across surface systems, and spatial and temporal scales complicate detection of drivers and effects. For example, drying of land surface due to permafrost degradation may cause an increase in wildfires, in turn resulting in a loss of ground surface insulation and change in surface albedo that accelerates permafrost thawing (Rowland *et al.*, 2010; Forkel *et al.*, 2012).

18.3.1.4. Erosion, Landslides, and Avalanches

Erosion and landsliding typically increases during phases of deglaciation in mountain areas (Ballantyne, 2002; Korup *et al.*, 2012) and there is emerging evidence for this to occur during contemporary deglaciation (Schneider *et al.*, 2011; Uhlmann *et al.*, 2012). Erosion related to sediment flux changes from mountain areas has been observed in the Western Himalaya in relation with hydrologic extreme events (medium confidence, Wulf *et al.*, 2012), increasing over the past 60 years (Malik *et al.*, 2011), with important impacts on hydropower schemes. For southern China, there is robust evidence of decline in sediment load in some rivers since the 1980s and 1990s (Zhang *et al.*, 2008a). Dam construction is an important driver of the recent decline in sediment load, leaving only *low confidence* in attributing the change to any climate impacts for the Yangtze catchment in China (Xu *et al.*, 2008).

Changes in sediment yield, e.g. from rockfall or disintegration of rock glaciers, related or unrelated to climate impacts, can significantly influence frequency and magnitude of alpine shallow landslides and debris flows (Lugon and Stoffel, 2010), but no clear evidence exists so far for a change in frequency of shallow landslides and debris flows from recently deglaciated mountain areas in the European Alps (Jomelli *et al.*, 2004; Stoffel and Huggel, 2012).

Rock slope failures in mountain areas with permafrost occurrence have increased since the 1990s (*high confidence* in the Western European Alps, *medium confidence* for New Zealand Alps, and *low confidence* globally). There also is *high confidence* that glacier retreat and downwasting, permafrost degradation and high-temperature events have contributed to many high-mountain rock slope failures over the past 20 years (Allen *et al.*, 2010; Ravanel and Deline, 2011; Schneider *et al.*, 2011; Fischer *et al.*, 2012; Huggel *et al.*, 2012a). Damages and costs for risk reduction measures in Alpine areas have increased due to rock fall and debris flows, with climate change playing a major role in triggering complex downstream impact chains and feedback (*medium to high confidence* of influence of anthropogenic climate forcing), such as recently documented in the Swiss Alps with costs on the order of tens of millions USD (Huggel *et al.*, 2012b). Rock and ice avalanches, and other landslides from destabilized slopes have also impacted glacier lakes and caused downstream damage in several high-mountain regions (e.g., Xin *et al.*, 2008; Bajracharya and Mool, 2009; Künzler *et al.*, 2010; Carey *et al.*, 2012a; Huggel *et al.*, 2012b).

Other than for the above mentioned types of landslides, there is no clear evidence that their frequency or magnitude has changed over the past decades (Huggel *et al.*, 2012b). This is true for shallow landslides and also for regions with a relatively complete event record (e.g. Switzerland, see Hilker *et al.*, 2009). In general, detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology. In line with loss from other extreme events (see 18.4.4) an increase in terms of casualties, or loss due to landslides has been documented in South, East and South-East Asia over the past years, but are largely attributed to changes in exposure, i.e. population growth (Petley, 2010).

No change in snow avalanche activity has been detected so far in Europe (Laternser and Schneebeli, 2002; Voigt *et al*., 2011). However, the detection of changes in snow avalanche impacts, such as fatalities and property loss, is difficult over the past decades due to changes in snow sport activities and avalanche defense measures.

18.3.2. Terrestrial and Inland Water Systems

As documented by previous IPCC reports (notably Rosenzweig *et al*., 2007), numerous changes in terrestrial and inland water systems have been attributed to recent climate change. Confidence in such detection of change is often *very high,* reflecting high agreement among many independent sources of evidence of change, and robust evidence that changes in ecosystems or species are outside of their natural variation. Confidence in attribution to climate change is also often *high*, due to process understanding of responses to climate change, or strong correlations with climate trends and where confounding factors are understood to have limited importance. The scientific literature in this field is growing quickly, precluding a full review in this chapter. Therefore, statements of confidence for detection and attribution are given without references, as detailed traceability is provided in chapter 4.

Organisms respond to changing climate in a multitude of ways, including through their phenology (the timing of key life history events such as flowering in plants or migration of birds), productivity (the assimilation of carbon and nutrients in biomass), spatial distribution, mortality / extinction, or by invading new territory. Noticeable changes may occur at the level of individual organisms, ecosystems, landscapes, or by modification of entire biomes. Organisms and ecosystems are adapted to a variable environment, and they are capable to adapt to gradual change to some degree – for the scope of this chapter, available knowledge will be reviewed concerning changes in terrestrial and freshwater ecosystems that occur beyond natural variability and which can be assumed to be due to recent climate change and/or increased in atmospheric CO_2. Confidence in the detection of such change involves therefore assumptions about natural variability in these ecosystems, and confidence in the attribution of detected change to climate drivers (or CO_2) implies the assessment of confounding drivers such as land use change.

18.3.2.1. Phenology

Since the AR4 there has been a further significant increase in observations of phenology of plants and animals, showing that many, but not all species have changed functioning to some degree over the last decades to centuries on all continents (*high confidence* due to robust evidence but only moderate agreement across all species). New satellite-based analyses confirm earlier trends, showing, for example, that the onset of the growing season in the northern hemisphere has advanced by 5.4 days from 1982 to 2008 and its end has been delayed by 6.6 days (Jeong *et al*., 2011). Significant changes have been detected, by direct observation, for many different species, for example, for amphibians, birds (breeding, migration), mammals, and plants; a number of meta-analyses have been carried out summarizing this literature (e.g., Cook *et al*., 2012). Attribution of these changes to climate change is supported by more refined analyses that consider also the regional changes in several variables such as temperature, growing season length, precipitation, snow cover duration and others, as well as experimental evidence. The *high confidence* in attributing many observed changes in phenology to changing climate is a result of these analyses, as well as of improved knowledge of confounding factors such as land use and land management (for more references and details see 4.3.2.1).

18.3.2.2. Productivity and Biomass

Many terrestrial ecosystems are now net sinks for carbon over much of the Northern hemisphere and also in parts of the Southern hemisphere (*high confidence*). This is shown, for example, by inference from atmospheric chemistry, but also by direct observations of increased tree growth in many regions including Europe, the United States, tropical Africa and the Amazon. During the decade 2000 to 2009, global land net primary productivity was approx. 5% above the preindustrial level, contributing to a net carbon sink on land of 2.6 ± 0.7 Pg C yr^{-1} (Raupach *et al*., 2008; Le Quéré *et al*., 2009, WGI AR5 Chapter 6), despite ongoing deforestation. These trends are in part due to nitrogen deposition, afforestation and altered land management which makes direct attribution of the increase to

climate change difficult (*low confidence* in attribution). The degree to which rising atmospheric CO_2 concentrations contribute to this trend remains a particularly important source of uncertainty (for more references and details, see 4.3.2.2 and 4.3.2.3).

18.3.2.3. Biodiversity

Each species responds differently to a changing environment, therefore the composition of species, genotypes, communities and even ecosystems varies in different ways from place to place, in response to climate change. The consequences are changing ranges of species, changing composition of the local species pool, invasions, mortality and ultimately extinctions. For different species and species groups, detected range shifts vary, and so do the confidence of detection and the degree of attribution to climate change. The number of species studied has considerably increased since the AR4. Overall, many terrestrial species have recently moved, on a global average, 17 km poleward and 11 m up in altitude per decade (e.g., Europe, North America, Chile, Malaysia), which corresponds to predicted range shifts due to warming (Chen *et al.*, 2011) and is 2 to 3 times faster than previous estimates (Parmesan and Yohe, 2003; Fischlin *et al.*, 2007), *high confidence* in detection. For example, over the last decades, arthropods have moved large and statistically significant distances towards the poles (many 10s of km). Species with short life cycles and high dispersal capacity – such as butterflies (*high confidence* in attribution) – are generally tracking climate more closely than longer-lived species or those with more limited dispersal such as trees (*medium confidence* in attribution). There are many less well-studied species for which detection of change and its attribution to climate change are more uncertain.

Across the world, species extinctions are at or above the highest rates of species extinction in the fossil record (*high confidence* in detection). However, only a small fraction of observed species extinctions have been attributed to climate change — most have been ascribed to non-climatic factors such as invasive species, overexploitation or habitat loss (*very low confidence* in attribution to climate change). For those species where climate change has been invoked as a causal factor in extinction (such as for the case of Central American amphibians), there is *low agreement* among investigators concerning the importance of climate variation in driving extinction and even less agreement that extinctions were caused by global warming. *Confidence* in the attribution of extinctions across all species to climate change is *very low*.

Species invasions have been increasing over the last several decades world-wide, notably in freshwater ecosystems (*very high confidence*), often causing biodiversity loss or other negative impacts. While there is a documented contribution of recent climate trends to establishment, growth, spread and survival of some invasive species populations, there is only *low confidence* that the species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated dispersal in mediating invasions (for more references and details see 4.3.2.5 and 4.3.2.6).

18.3.2.4. Impacts on Major Systems

The extent of recent change in major ecosystems such as the boreal forest, the Arctic tundra, or the Amazon forest has been characterized as a “regime shift” by some authors (e.g., Biggs *et al.*, 2009), implying significant and broad-scale changes in both distribution and functioning of the ecosystem.

Field and satellite measurements indicate a substantial increase in shrub growth (often linked to permafrost thawing) in many areas of the Arctic tundra (*high confidence* in detection). This change corresponds to expectations, based on experiments, models and paleoecological responses to past warming, of broad-scale boreal forest encroachment into tundra, a process which takes decades and which would have very large impacts on ecosystem structure and function. The particular strength of warming over the last 50 years for most of the Arctic further facilitates attribution (*high confidence*). The change affects a significant area of the tundra biome and can be considered an early warning for an upcoming regime shift.

For the boreal forest, increases in tree mortality are observed in many regions, including wide-spread dieback related to insect infestations in North America, but there is *low confidence* in detection of a global trend. Local and regional mortality has in some cases been linked to climate fluctuations, but there is *low confidence* in attributing any perceived overall dieback to climate change. At the Southern "trailing end" of the shifting boreal zone, there are indications of enhanced mortality of plant species (notably trees), but there is *low confidence* in overall detection due to a lack of temporal and spatial coverage of observations. There is consequently also *low confidence* in attribution of the changes to climatic change.

In the humid tropical forests of the Amazon basin, increases in tree turnover (increased mortality and growth) have been detected with *medium confidence* for recent decades. These changes have been explained by a number of factors, including the direct effect of rising CO_2 on lianas, recovery from past disturbance and changing climate. Overall, there is *very low confidence* in attribution of these observations to climate change.

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in invertebrate and fish community composition, especially in headwater streams where species are more sensitive to warming (*high confidence* in detection, *low confidence* in attribution due to numerous confounding factors; 4.3.3.1, 4.3.3.3).

18.3.3. Coastal Systems and Low Lying Areas

In coastal waters, both average warming rate and changes in seasonal timing are larger than in the open oceans (see 5.3.3). Sea surface temperatures have warmed significantly during the past 30 years along more than 70% of the world's coastlines, albeit with large spatial and seasonal variation in the rates of change *(very high confidence)*. The frequency of extreme temperature events has changed in many areas (Lima and Wethey, 2012). Seawater pH also spans larger ranges and exhibits higher variability near coastlines, and anthropogenic ocean acidification can be enhanced or lessened by coastal geochemical processes (Borges and Gypens, 2010; Feely *et al*., 2010; Duarte *et al*., 2013, see also Box CC-OA), and extreme winds, changes in wave regime and sea level play important roles in coastal processes (seeTable 5-1).

While it is *extremely likely* that observed global sea level rise can at least in part be attributed to anthropogenic emissions (WGI AR5 Chapter 10.4.3), the evaluation of local sea level trends must consider important local confounding factors, such as regional variability in ocean and atmospheric circulation, subsidence, coastal erosion, and coastal modification (see also 5.3.2). Thus far, it has not been possible to isolate an anthropogenic climate signal in local sea level changes from the contributions of these confounding factors. A possible emerging exception is along the coasts of regions with melting glaciers and ice sheets, where local gravitational effects leading to a lowering of sea level may dominate other factors (Kopp *et al*., 2010; Tamisiea and Mitrovica, 2011). As a consequence, attribution of observed effects of relative sea level change to climate change is hardly possible (see Nicholls *et al*., 2007; Nicholls *et al*., 2009), despite attempts for very few locations, e.g. for flood damages in Venice (Carbognin *et al*., 2010).

18.3.3.1.Erosion, Shoreline Processes, and Coastal Aquifers

Throughout the world, beaches and dunes, as well as bluffs and cliffs, are eroding due to a variety of climate related processes, such as rising mean sea levels (Leatherman *et al*., 2000; Ranasinghe and Stive, 2009), more frequent extreme sea levels (Woodworth *et al*., 2011), changes in wave regimes (Tamura *et al*., 2010; Reguero *et al*., 2013), the loss of natural protective structures such as coral reefs (Grevelle and Mimura, 2008) or mangrove forests due to increased ocean temperatures or ocean acidification (Bongaerts *et al*., 2010), or permafrost degradation and sea ice retreat (Manson and Solomon, 2007). However, there are multiple non-climate related drivers involved in shoreline erosion, including dams capturing fluvial sands, subsidence due to resource extraction, mining and coastal engineering and development. Due to the fragmentary nature of the information available and to the multiple natural and anthropic stressors contributing to coastal erosion, confidence in attribution of shoreline changes to climate change is *very low*, with the exception of polar regions (Forbes, 2011, see also 18.5).

Coastal lagoons and estuaries, as well as deltas are highly susceptible to alterations of sediment input and accumulation (Syvitski *et al.*, 2005; Ravens *et al.*, 2009), processes that can be influenced by climate change via changes in sea level, storminess, and precipitation. However, the primary drivers of widespread observed changes in those systems are human drivers other than climate change (thereby *very low confidence* in attribution to climate change, see 5.4.2.6, 5.4.2.7).

Coastal aquifers are crucial for the water supply of densely populated coastal areas, in particular in Small Island environments. Aquifer recharge is sensitive to changes in temperature and precipitation; and rising sea levels and sea water overwash from storm surges can contribute to saline intrusion into groundwater (Post and Abarca, 2010; Terry and Falkland, 2010; White and Falkland, 2010, see also 29.3, Table 18-8). However, excessive groundwater extraction for coastal settlements and agriculture is the main cause for widely observed groundwater degradation in coastal aquifers (e.g., White *et al.*, 2007a; Barlow and Reichard, 2010). Attribution to climate change, in particular incremental sea level rise, is not supported in the literature (Rozell and Wong, 2010; White and Falkland, 2010).

18.3.3.2. Coastal Ecosystems

Coastal habitats and ecosystems experience cumulative impacts of land- and ocean-based anthropogenic stressors (Halpern *et al.*, 2008). Most coral reefs, seagrass beds, mangroves, rocky reefs and shelves have undergone substantial changes. Coral reefs have been degraded due to both local anthropogenic factors such as unsustainable fishing and pollution, and global change factors such as increased heat waves, ocean warming and acidification (see also Box CC_CR). Coral bleaching is being detected with *high confidence* on all coasts, and warming is a major contributor (*high confidence*, for further discussion see Box 18-3, and Box CC_OA). Overexploitation and habitat destruction have been responsible for a large fraction of historical changes observed in coastal ecosystems (Lotze *et al.*, 2006).

Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2011). Increased loads of nutrients from anthropogenic sources generate coastal eutrophication and constitute the primary cause of increasing hypoxia, while upwelling of low oxygen waters and ocean warming constitute secondary drivers (see Zhang *et al.*, 2010). Persisting hypoxia can result in so-called "dead zones", which have approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008).

Changes in abundance and distribution of rocky shore species have been observed since the late 1940s in the North East Atlantic (Hawkins *et al.*, 2008), and the role of temperature has been demonstrated by experiments (e.g., Peck *et al.*, 2009; Somero, 2012, see also 5.4.2.2). Distinguishing the response to climatic stressors from changes due to hydrology, or natural temporal and spatial fluctuations, is nevertheless challenging.

Globally, the range limits of many intertidal species have shifted up to 50 km per decade, much faster than most recorded shifts of terrestrial species (Helmuth *et al.*, 2006, see also Box 18-4). However, the geographical distribution of some species did not change in the past decades. This may be due to weak local warming (Rivadeneira and Fernández, 2005), or overriding effects of variables such as timing of low tide, hydrographic features, lack of suitable bottom types, larval dispersal, food supply, predation and competition (Helmuth *et al.*, 2002; Helmuth *et al.*, 2006; Poloczanska *et al.*, 2011). Changes in current patterns and increased storminess can dislodge benthic invertebrates and affect the distribution of propagules and recruitment.

Changes in musselbeds in response to higher temperatures induced by climatic change have been observed along the West coasts of the United States (Smith *et al.*, 2006a; Menge *et al.*, 2008; Harley, 2011). On Tatoosh Island (Washington, USA), a shift in community structure from a mussel to an algal-barnacle-dominated community has been attributed to rapidly declining pH (Wootton *et al.*, 2008; Wootton and Pfister, 2012).

Ocean warming is also leading to range shifts in vegetated coastal habitats such as coastal wetlands, mangrove forests and seagrass meadows (*medium confidence*, see 5.4.2.3). Extreme temperature events can alter marine and

coastal communities, as shown for the European heatwave 2003 (Garrabou *et al*., 2009), and the early 2011 heat wave off the Australian West Coast (Wernberg *et al*., 2012).

Poleward expansion of mangrove forests, consistent with expected behavior under climate change, has been observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux *et al*., 2011; Raabe *et al*., 2012), and New Zealand (Stokes *et al*., 2010). High temperatures have impacted seagrass biomass in the Atlantic Ocean (Reusch *et al*., 2005; Díez *et al*., 2012; Lamela-Silvarrey *et al*., 2012), the Mediterranean Sea (Marbà and Duarte, 2010) and Australian waters (Rasheed and Unsworth, 2011). Extreme weather events contributed to the overall degradation of seagrass meadows in a Portuguese estuary (Cardoso *et al*., 2008).

Decline in kelp populations attributed to ocean warming has occurred off the North coast of Spain (Fernández, 2011), as well as in southern Australia, where the poleward range expansion of some herbivores have also contributed to observed kelp decline (Johnson *et al*., 2011; Wernberg *et al*., 2011; Wernberg *et al*., 2011). The spread of subtropical invasive macroalgal species (e.g., Lima *et al*., 2007) may be adding to the stresses temperate seagrass meadows experience from ocean warming.

Overall, there is *high confidence* in detection of range shifts and biodiversity changes in intertidal and other coastal species, as well as in a decline in kelp forests, and increased mortality of seagrasses, and *high confidence* that climate change has contributed to these effects (5.4.4, Figure 5-5). For the widespread decline observed in salt marshes and mangroves, there is *very low confidence* in a role of climate change due to overriding effects of other human drivers.

18.3.3.3. Coastal Settlements, Infrastructure, and Economic Activities

Recent global (e.g., Menéndez and Woodworth, 2010; Woodworth *et al*., 2011) and regional studies (e.g., Marcos *et al*., 2009; Haigh *et al*., 2010; Haigh *et al*., 2011) have found that observed trends in extreme sea levels are mainly consistent with mean sea level trends (Woodworth *et al*., 2011), indicating that the increasing frequency of extreme events affecting coastal infrastructures observed so far is related to rising mean sea level rather than to changes in the behaviour of severe storms. Increased damages from coastal flooding have been observed with *high confidence*, however, with exposure and subsidence constituting the major drivers, confidence in attribution to climate change is *very low* (Seneviratne *et al*., 2012, see also 5.4.3, 5.4.4).

Increases in saltwater intrusion and flooding have been observed in low-lying agricultural areas of deltaic regions and Small Islands, but the contribution of climate change to this is not clear (e.g., Rahman *et al*., 2011, see also 18.5.9). Both climate variability and change impact fishermen livelihoods (Badjeck *et al*., 2010) and physiological and ecological properties of fish (e.g., Barange and Perry, 2009, see also 18.3.4, 18.4.1.2); however local and regional observations of climate impacts on output of coastal fisheries are scarce.

While vulnerability of coastal settlements and infrastructure to future climate change, in particular sea level rise and coastal flooding, is widely accepted and well-documented (seeTable 5-5), there is a shortage of studies on the role of climate change in observed impacts on coastal systems.

_____ START BOX 18-3 HERE _____

Box 18-3. Detection and Attribution of Mass Coral Bleaching and Mortality to Climate Change

Declining water quality as well as increasing fishing pressure and coastal development have been implicated in the rapid decline in the abundance of corals and coral reefs over the past 50 years (Bryant *et al*., 1998; Gardner *et al*., 2003; Bruno and Selig, 2007; Sheppard *et al*., 2010; Burke *et al*., 2011; De'ath *et al*., 2012). Since 1980, mass coral bleaching and mortality events began to occur on reefs throughout the tropics and subtropics with no precedent in the scientific literature (Box CC-CR). While bleaching of individual coral colonies has been reported prior to 1980 (Yonge and Nichols, 1931), mass coral bleaching events involving hundreds and thousands of coral colonies across entire reef and coastal regions have not (Hoegh-Guldberg, 1999; Baker *et al*., 2008). These novel events are often

followed by the mass mortality of coral communities, especially if conditions remain anomalously warm for long periods (ibid). In the very warm year of 1998, for example, mass coral bleaching affected almost every part of the seas associated with the tropics and subtropics resulting in the loss of 16% of the world's reef-building coral (Wilkinson and Hodgson, 1999).

There is broad agreement that mass coral bleaching can be triggered by small increases in sea temperature (> 1°C) above the summer maxima for a region over several weeks (very high confidence, Hoegh-Guldberg, 1999; Baker *et al.*, 2008; Strong *et al.*, 2011). The impact of temperature is also exacerbated by strong solar irradiance (Hoegh-Guldberg, 1999). There is also broad agreement that thermal stress impacts the ability of *Symbiodinium* to capture and process light, leading to the production of damaging reactive oxygen species which precedes the loss of symbionts (Jones *et al.*, 1998). As the symbiosis breaks down, the brown dinoflagellates leave their host corals, turning their tissues white and depriving corals of an important source of energy (Muscatine, 1986; Hoegh-Guldberg and Smith, 1989).

There is little or no evidence that reef-building corals and their *Symbiodinium* have, or evolved substantially in terms of the thermal tolerance over yearly or decadal time frames, or can be expected to do so (Hoegh-Guldberg, 2012). The relationship between elevated sea temperatures and mass coral bleaching remains robust enough to be used within algorithms that reliably detect and project the incidence of mass coral bleaching from satellites (Strong *et al.*, 2004; Strong *et al.*, 2011). Depending on the size of the thermal anomaly and exposure time, communities of reef-building corals have either recovered, or have experienced large-scale mortalities such as those seen worldwide in 1998 (Hoegh-Guldberg, 1999; Wilkinson and Hodgson, 1999; Baker *et al.*, 2008) and 2005 in the Caribbean (Eakin *et al.*, 2010). The detection of mass coral bleaching has been improved using satellite algorithms such as Degree Heating Weeks (DHW) (ibid).

Of the many variables investigated, only elevated sea temperature co-occurs consistently with mass coral bleaching and mortality events, and has a well worked physiological model associated with it (Hoegh-Guldberg, 1999). Consequently, given the relationship between global climate change and increased ocean temperatures, and that between coral bleaching and elevated temperature, the detected increase in the frequency of mass coral bleaching and mortality events can be attributed to anthropogenic climate change as the dominant driver with *very high confidence*.

_____ END BOX 18-3 HERE _____

18.3.4. Oceans

Since 1970, ocean temperatures have increased by around 0.1°C decade^{-1} in the upper 75 m and approximately 0.02°C decade^{-1} in the upper 500m, due to anthropogenic warming.

The increased flux of CO_2 from the atmosphere to the ocean has reduced the average pH of seawater by 0.1 pH units over the past century, with the greatest reduction occurring at high latitudes (Box CC-OA). These changes have been attributed to increases in the atmospheric concentration of greenhouse gases as result of human activities (*high to very high confidence*, WGI AR5 Chapter 10.4.1-10.4.4). Changes in wind speed, upwelling, water column stratification, surface salinity, ocean currents, solar irradiance, cloud distribution, and oxygen depth profile have also occurred (WGI AR5 Chapter 3.2 – 3.8; Figure 30-5, 30-6, 30-7).

Changes in the physical and chemical nature of ocean environments are predicted to have impacts on marine organisms and ecosystems, with many already having been observed across most ocean regions (see 6.2, 6.3, 6.5, 30.4, 30.5). However, the detection and attribution of recent changes in ocean systems is complicated by the influence of long-term variability such as the Pacific Decadal Oscillation (PDO), El Niño-Southern Oscillation (ENSO), and the Atlantic Multidecadal Oscillation (AMO). The fragmentary nature of ocean observations and the influence of confounding factors such as fishing, habitat alteration, and pollution also represent significant challenges to detection and attribution (Hoegh-Guldberg *et al.*, 2011; Parmesan *et al.*, 2011).

18.3.4.1. Impacts on Ocean System Properties and Marine Organisms and Ecosystems

Greater thermal stratification in many regions has reduced ocean ventilation and mixing depth, thereby reducing the availability of inorganic nutrients and hence primary productivity in surface layers, with controversial trends depending on methodology (see 6.1.3, 6.2.3, 30.5.6). However, upwelling has increased in some regions bringing greater concentrations of nutrients to surface waters, boosting productivity (see 30.5.5) and enhancing fisheries output (see also 18.4.1.2 for fisheries). Increases in productivity also occurred with warming and sea ice loss at high latitude. At a global scale a small increase in net primary production has been detected (Table 18-1, *medium confidence*).

Poleward shifts in the distributions of zooplankton, fish, seabirds and benthic invertebrate have been observed, particularly from the well-studied NE Atlantic, with a clear attribution to warming (*high confidence*, 6.3.2, 30.5.1). In many regions, Temperature exerts the strongest influence on ecosystems and the responses of ecological systems to changing temperature are well-studied. However, it is often difficult to clearly identify the interaction of temperature with other factors (6.3.5). Some studies have found changes in the abundance of fish species that are consistent with regional warming, with differences in response between species, in line with differential specializations of coexisting species (6.2, 6.3.2, Pörtner, 2012). Anthropogenic influences modulate responses to climate, e.g., due to exploitation status (Tasker, 2008; Belkin, 2009; Overland *et al*., 2010; Schwing *et al*., 2010), with more heavily exploited species being more sensitive to environmental variability in general, including temperature trends and extremes (Hsieh *et al*., 2005; Stige *et al*., 2006; Hsieh *et al*., 2008).

Changes to water column mixing have combined with other factors such as nutrient loading to drive down oxygen concentrations and increase the number and extent of hypoxic zones. These zones are characterized by very low oxygen and high CO_2 levels and have been detected with *high confidence*, and attributed in part to enhanced stratification and microbial respiration caused by warming *(medium confidence,* see Table 18-1). In some cases, expanding or shifted hypoxia exerts strong local and regional effects on marine biota such as distribution shifts, habitat contraction or loss, and fish kills.

Laboratory experiments have shown that a broad range of marine organisms (e.g. corals, fish, pteropods coccolithophores, and macroalgae), physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth and neural function), and ecosystems processes (e.g., productivity, reef building and erosion) are sensitive to changes in pH and carbonate chemistry of seawater (*high confidence*, 6.2.2-5, 6.3.4, Box CC-OA). However, few field studies have been able to detect and attribute specific changes in marine ecosystems to anthropogenic ocean acidification due to the inability to identify the effect of ocean acidification from ocean warming or local factors (Wootton *et al*., 2008; De Moel *et al*., 2009; Moy *et al*., 2009; Bednaršek *et al*., 2012, see also 6.3.4).

[INSERT TABLE 18-1 HERE
Table 18-1: Observed changes in ocean system properties and their effects, with confidence levels for detection and attribution to climate change, based on assessment in Chapter 6.2, 6.3, and summarized in 6.6.1 and Figure 6-16. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.]

There has been a substantial increase in the number of studies documenting significant changes in marine species and processes since the AR4 (Hoegh-Guldberg and Bruno, 2010). A new meta-analysis using a database of long-term observations from peer-reviewed studies of biological systems, with nearly half of the time series extending prior to 1960, shows that a high proportion (81%) of observed responses are consistent with regional climate change (see 30.4). Poloczanska *et al*. (2013) argue that the high consistency of marine species' responses across geographic regions (coastal to open ocean, polar to tropical), taxonomic groups (phytoplankton to top predators), and types of responses (distribution, phenology, abundance) reported in their analysis support the detection of a widespread impact of climate change on marine populations and ecosystems (see 30.4 and 30.5 for more detail).

The impacts of climate change on marine organisms such as fish, invertebrates and marine algae include changes in abundance, distribution, and community structure and shifts in phenology and migration patterns. Table 18-2 gives examples of the manifestation of climate change on marine species.

[INSERT TABLE 18-2 HERE
Table 18-2: Observed changes on marine species and ecosystems, with confidence levels for assessment of detection of changes and their attribution to climate change, based on assessment in Chapter 6.2, 6.3, summarized in 6.6.1 and Figure 6-16, and 30.4. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.]

18.3.4.2. Observed Climate Change Effects across Ocean Regions

While climate change is evident across the Ocean, its impacts vary between ocean regions (Table 30.2; Figures 30-2, 30.3 and 30.5; WGI AR5 Chapter 3). Considerable differences in system understanding, data availability, and the potential contribution of climate change in relation to other factors add to the heterogeneity of the assessment. Attribution of regional heat content changes are less certain than on a global level, but warming patterns have been detected in all basins (Table 30-2, Figure 30-2) and attributed to anthropogenic influence with *high confidence* (WGI AR5 Chapters 3, 10.3.1, and 10.4), with the important exception of Eastern Boundary Upwelling Ecosystems (EBUE), where two of the four major upwelling systems show no change in sea surface temperatures over the last 60 years (table 30-2). These differences may relate to geographical differences that contribute to different levels of change in wind stress and hence upwelling, which influences the amount of cooler water flooding the surface layers of the water column in these regions (see Box 30.8.2). Recent research shows deep penetration of warming in some regions, and declining oxygen levels *(low to medium confidence*, see Table 18-3). Regional estimates of CO_2 uptake are in line with global estimates, and ocean acidification has been detected and attributed with *high confidence* in most regions (WGI AR5 Chapter 3.8.1, 30.5, Box CC-CAO). Table 18-3 shows confidence in detection and attribution of observed climate change impacts across the world's major open ocean regions, with the exception of the Deep Sea.

[INSERT TABLE 18-3 HERE
Table 18-3: Confidence in detection and attribution of observed climate change effects across ocean regions, based on expert assessment in Chapter 30.5 (respective subsections are given below). Confidence levels assigned are for detection / attribution, respectively.]

The high latitude spring bloom systems of the Northern Hemisphere show strong warming and associated effects (see above). In the North Pacific, the Bering Sea is one of the productive sub-regions and has undergone major changes in recent decades as a result of climate variability, climate change and fishing impacts (Litzow *et al*., 2008; Mueter and Litzow, 2008; Jin *et al*., 2009; Hunt, 2010). Loss of sea ice has led to the retreat of the cold pool in the Bering Sea, and northward expansion of productivity.

Marginal seas such as the East China Sea are also warming rapidly. There is *high confidence* that this has contributed to declining primary productivity and fisheries yields as well as other ecological changes (30.5.4.1). However, other human pressures including over-fishing, habitat alteration, and nutrient loading are important contributing factors and it is difficult to disentangle these from the impacts of climate change.

Semi-enclosed seas like the Black and Baltic Seas and the Arabian / Persian Gulf have their own specific environmental conditions and responses (30.5.3.1). The Baltic and Black Seas show an expansion of hypoxic zones attributed in part to climate change (*medium confidence*). Coral reefs in the Arabian / Persian Gulf and Red Seas appear to have experienced widespread bleaching in 1996 and 1998 associated with elevated temperature. It is highly likely that these impacts are associated with long-term variability that has, combined with climate change, resulted in warmer than normal summer sea temperatures that now periodically exceed the thermal tolerance of reef-building corals (*high confidence*).

Warming of the Mediterranean has been associated with mass mortality events as well as with invasions and subsequent spread of new warm water species, which has resulted in the 'tropicalisation' of fauna (30.5.3.1.3). In many tropical regions and the subtropical gyres of the Pacific, Indian, and Atlantic, periodic heat stress combined with other local stresses has driven mass coral bleaching and mortality (see also Box CC-CR, 30.5).

In other regions, such as the California Current upwelling system, high-quality databases support *very high confidence* in the detection of ecological changes, but attribution of these to climate change can be made with *very low confidence* due to large-scale environmental variability associated with ENSO and the PDO.

In overall terms, attributing observed local and regional changes in marine species and ecosystems to climate change remains an important question for on-going research (Stock *et al*., 2010).

_____ START BOX 18-4 HERE _____

Box 18-4. Differences in Detection and Attribution of Ecosystem Change on Land and in the Ocean

Marine and terrestrial ecosystems differ in fundamental ways. Gradients in turbulence, light, pressure and nutrients uniquely drive fundamental characteristics of organisms and ecosystems in the ocean. While the critical factor for transporting nutrients to marine primary producers ocean mixing driven by wind, water is the primary mode for transporting nutrients to land plants. In addition to these characteristics, marine ecosystems are often more technically difficult and costly to explore than terrestrial equivalents, which explains the low number and shorter scientific studies of marine ecosystems (Hoegh-Guldberg and Bruno, 2010). The latter has restricted the extent to which we can accurately detect and attribute of changes within the Ocean.

Impacts of climate change in terrestrial and marine systems differ significantly for the same types of measures, e.g., species phenology and range shifts, leading to differences in expert's interpretations of the data and possibly divergent levels of confidence in detection and attribution. There are also fundamental differences in exposure of organisms to recent warming, their biological responses and our ability to detect change through observations. Changes in temperature of ocean systems have generally been less than those of terrestrial ecosystems over the last four decades (Burrows *et al*., 2011). Furthermore, despite higher variability the horizontal spatial gradient of temperature change (°C km^{-1}) is generally much higher in terrestrial ecosystems than in marine ecosystems. All else being equal, the net result is that species have generally needed to move much shorter distances in terrestrial ecosystems to stay within their preferred climates, also due to the influence of the topography such as mountain ranges (Burrows *et al*., 2011), although many marine species can potentially exploit strong vertical thermal gradients to attenuate the need for range shifts in response to warming.

Species and ecosystems may respond very differently to these climate signals in ways that influence the ability to detect change. For example, a comparison of ectotherm species (i.e., species that do not actively regulate their body temperatures such as reptiles and fish) indicates that marine species' ranges have tracked recent warming at both their poleward and equatorial range limits, while many other terrestrial species' ranges have only tracked warming at their poleward range limits (Sunday *et al*., 2012). Biological processes influencing phenological shifts may also differ substantially between systems. For example, the effect of climate on the timing of flowering of terrestrial plants at high latitudes is only moderately influenced by confounding effects, whereas the timing of phytoplankton blooms in high latitude marine systems is highly dependant on ocean temperature and associated stratification and changes in nutrient availability.

_____ End BOX 18-4 HERE _____

18.4. Detection and Attribution of Observed Climate Change Impacts in Human and Managed Systems

Observed impacts on human systems have received considerably less attention in previous IPCC reports and the scientific literature, compared to observed impacts on natural systems. Human systems' "normal state in the absence of climate change" is almost never stationary. Confounders other than climate change have been and continue to

drive the normal evolution of these systems with climate often playing a relatively minor role. It is therefore difficult to detect and attribute the signal of climate change in the majority of human systems. The food system is one noteworthy exception. There is emerging literature estimating the climate *sensitivity* of many sectors within the human system, yet climate impacts are often not detectable over the impacts from non-climate confounders.

For some human systems, the only observed situations where a climate signal had a detectable and sometimes attributable impact are during extreme weather events. Extreme events for a variety of sectors are therefore discussed in a single section below. Overall, the literature has made significant progress for certain sectors, such as food systems, since AR4. The following sections provide a synthesis of findings with regard to food systems, cities, economic systems, human health, human security and human livelihoods and poverty, which are documented in greater detail in chapters 7, 8, 9, 10, 11, 12 and 13. We have also incorporated evidence from regional chapters and further available literature, especially for the discussion of extreme events, human security, and observed changes in indigenous communities.

18.4.1. Food Production Systems

Over the past several decades food production systems across the globe have changed significantly. Factors other than atmospheric CO_2 or climate, such as cultivar improvement and increased use of synthetic fertilizers, herbicides, and irrigation were primarily responsible for these changes. In a number of settings the effects of past changes in weather or CO_2 have been regarded as noise that obscures other effects of interest (Bell and Fischer, 1994). Due to the large number and relative importance of non-climate drivers in food systems and food security, formal detection and attribution of impacts is extremely difficult for this sector. The majority of confounders, such as fertilizer application or adoption of modern crop varieties, are not well measured in terms of their distribution across space and time. Further, it is difficult to quantify the exact relationship between these confounders and outcomes of interest (e.g., crop yields). The identification of a unique fingerprint from greenhouse gas emissions in these systems is therefore impractical. There are no known studies simulating historical trends in food-related outcomes with and without changes in anthropogenic emissions of greenhouse gases. A possible exception is the study by Auffhammer et al. (2006) who compared predicted rice yields in India using climate model simulations of temperature in the late 20^{th} century with yields estimated from observed temperatures for 1930-1960, using the latter period as a surrogate for climate without recent changes in greenhouse gases. They find that rice yields in a world without greenhouse gas emissions would have been significantly higher, thus attributing negative impacts to emissions.

18.4.1.1. Agricultural Crops

In order to make attribution statements regarding crop changes to climate change, one needs to make assumptions about how farmers adapt. Some studies assume that farmers do not change their practices or technology as a response to changes in climate during the period of study. This may be a valid assumption in some cases (Schlenker and Roberts, 2009) yet there is evidence of significant adaptation to climate via technology for a variety of crops and locations (Zhang *et al*., 2008b; Liu *et al*., 2010).

A significant number of studies have provided impact estimates of observed changes in climate on cropping systems over the past few decades (see chapter 7.2). Based on this literature, there is *medium confidence* that over the past several decades observed climate trends have adversely affected wheat and maize production for many regions. There is *medium confidence* that observed climate trends since 1980 have had adverse impacts on global total production of these crops (Figure 7-2). There is *medium confidence* that climate change impacts on rice and soybean yields over this time period have been small in major production regions and globally (Figure 7-2). There is *high confidence* that in some cold regions warming has benefitted crop production in recent decades (Jaggard *et al*., 2007; Chen *et al*., 2011).

Many crop modeling studies focus on production for single sites or provinces and/or short time-series, rendering attribution of observed yields to climate change problematic. Some recent studies, however, examine outcomes at the continental or global scale (Lobell and Field, 2007; You *et al*., 2009; Lobell *et al*., 2011). At this scale, observed

trends in some climatic variables, including mean summer temperatures, can be attributed to anthropogenic activity (e.g., Jones *et al.*, 2008). These studies indicate that this observed warming has had significant negative impacts on trends in crop yields for certain crops. Figure 7-3 presents a summary of the detectability of changes in growing season climate and crop yield changes, as well as the ability to attribute changes to climate and CO_2 trends (in the case of yield changes) or anthropogenic emissions (in the case of growing season climate changes).

The recent literature has increasingly documented attibutable trends not only in the seasonal averages of climate variables, but also for extremes. Extreme rainfall events are widely recognized as important to cropping systems (Rosenzweig *et al.*, 2002). Changes in the patterns of rainfall extremes have been attributed to anthropogenic activity (Min *et al.*, 2011). A similar observation has been made for frost patterns in nearly every region of the world (Alexander *et al.*, 2006; Zwiers *et al.*, 2011), as well as for the occurrence of very hot nights (WGI AR5 Chapter 10.6.1). High nighttime temperatures are harmful to most crops, but this effect has been observed most frequently for rice yield (Peng *et al.*, 2004; Wassmann *et al.*, 2009; Welch *et al.*, 2010) and quality (Okada *et al.*, 2009). Daytime extreme heat is also damaging and sometimes lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009). At the global scale, trends in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Zwiers *et al.*, 2011).

Further, changing atmospheric conditions are affecting crops both positively and negatively. It is *virtually certain* that the dramatic increase in atmospheric CO_2 conentrations since preindustrial times has improved water use efficiency and yields most notably in C_3 crops. It is important to note that these effeects are of relatively minor importance when explaining total yield trends (Amthor, 2001; Long *et al.*, 2006; McGrath and Lobell, 2011).

Emissions of CO_2 have been associated with ozone (O_3) precursors (Morgan *et al.*, 2006; Mills *et al.*, 2007). There is *high confidence* that elevated O_3 currently suppresses global output of major crops, with reductions estimated at roughly 10% for wheat and soy and 3-5% for maize and rice (Van Dingenen *et al.*, 2009). Detected impacts are most significant for India and China, but can also be found for soybean production in the United States in recent decades (Fishman *et al.*, 2010).

18.4.1.2. Fisheries

There is a large literature focusing on the relationship between the dynamics of marine fish stocks and climate variability, suggesting that climate change has impacts on these stocks and on the fisheries that exploit them (Hollowed *et al.*, 2001; Roessig *et al.*, 2004; Shriver *et al.*, 2006; Brander, 2007). Some fisheries and aquaculture do not show evidence of climate change impacts (e.g. aquaculture in the UK and Ireland, Callaway *et al.*, 2012), while many others do with both positive and negative changes (30.6.2.1; Figure 30-15B, see also 18.3.4).

There is *high confidence* in the detection and attribution of shifts in the spatial distributions of marine fishes (Perry *et al.*, 2005, 30.6.2.1) and in the timing of events like spawning and migration (Sydeman and Bograd, 2009, 30.4). The challenges produced by ocean warming and acidification vary from region to region, however, with decreases in many regions and increases (probably short-term) in some regions, especially at high latitudes (30.6.2.1; Figure 30-15B). The ability to attribute detected changes to climate change is confounded by the influence of other factors such as harvesting, habitat modification, technological development, pollution, and interannual to decadal climate variability (Brander, 2010).

Ecosystems such as kelp forests, mangroves and coral reefs provide habitat to fisheries which provide food and income to hundreds of millions of people worldwide. The strong linkage between increasing sea temperatures, the decline of carbonate reef frameworks (see Box 18-3), and habitat for key fisheries resources underpins a strong traceable account from global climate change to impacts on coastal fisheries (*high confidence*; see Box CC-CR, Figure 30-12, 30.5.2 - 30.5.4, 30.5.6).

Similar linkages between climate change and fisheries can be made for pelagic fisheries such as tuna. Shifts in tuna fisheries have occurred in the Indian and Pacific oceans, driven by climate variability (ENSO). The detected changes

are consistent with the thermal biology of these important species and projections of change under further changes to ocean temperature (*high confidence*, 30.5.1.1.1, 30.5.6.1, 30.6.2.1).

18.4.1.3. Food Security

Food security depends crucially on the production and storage of food. The evidence on observed climate change impacts on food production therefore has implications for food security. Further, the term food security needs to be discussed at different spatial scales, as there is enough food available per capita globally, yet a significant share of humankind is affected by permanent or periodic food shortages. Quantifying the impact of climate change on food security is extremely challenging at any scale as there are significant numbers of non-climate confounders which affect food security at various spatial scales (7.1).

One measurable indicator of food security is the global price of food. Food prices have dropped slowly throughout the last century, yet even since AR4 there have been several periods of food price increase and periodic spikes in food prices (figure 7-4). Increased demand for crops recently has been partially driven by biofuel productions, which is both mandated by policy and market driven by oil price spikes (Roberts and Schlenker, 2010; Mueller *et al*., 2011; Wright, 2011). There is some evidence that supply side fluctuations also impacted food prices (figure 7.4). While not all significant weather events result in food price spikes, high price episodes are more probable during periods with low stored stocks. This can be due to more slowly growing supply relative to demand. Government interventions, such as export bans, can exacerbate price responses to weather events (Dawe, 2008). There is some recent evidence that climate trends have had some influence on global supply. Lobell *et al*. (2011) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO_2 over the study period were considered.

18.4.2. Cities and Urbanization

The world continues to urbanize rapidly. Both new and existing urban systems are evolving due to rapidly changing incomes, institutions and population. There is robust evidence across a set of case studies that climate has changed in many urban areas and that variability has increased, consistent with climate change projections. The most robust evidence has emerged from observational data for mean annual temperature and precipitation rates, days of extreme temperature, number of extreme rainfall events, and rate of sea level rise (8.2.2.1, 8.3). These shifts are associated with an increased probability of flooding, droughts, inland flooding, coastal flooding, storm surges, heat waves, and declines in the number of extreme cold days (see Hunt and Watkiss, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig *et al*., 2011for recent reviews).

Detection and attribution of climate change impacts in cities is extremely difficult due to the large role of other confounding factors. Opportunities to discern climate change signals in cities are complicated by the pattern and pace of urbanization which have consequences for local environmental conditions such as intensification of urban heat islands, land subsidence associated with groundwater withdrawal, and heightened flooding probability resulting from increase of impervious surfaces. These conditions interact with ongoing climate change and as a result make it difficult to provide evidence and attribution agreement of climate change signals in cities given the current state of observed data and models.

18.4.3. Economic Impacts, Key Economic Sectors and Services

18.4.3.1. Economic Growth

A negative cross sectional correlation between per capita income and temperature has been observed both across countries (Nordhaus, 2006) and across regions within countries (Dell *et al*., 2009a; Dell *et al*., 2009b). Such correlations should never be interpreted as causal, because the underlying mechanisms are usually complex. In low income countries, careful tracking of incomes and temperatures over an extended period, taking into account

important confounders, shows that higher annual temperatures as well as higher temperatures averaged over 15 year periods result in substantially lower economic growth (Dell *et al.*, 2012). This effect is not limited to the level of per capita income, but also to its rate of growth.

Broadly, a 1 degree Celsius increase in annual average temperature has been found to lower economic growth in the same year by 1.3%, which is both statistically and economically significant (Dell *et al.*, 2012). Based on 15 year averages of weather, which is a measure of climate, the impacts become larger (1.9% for low income countries). The same relationships do not hold for high income countries. Generally, higher temperatures affect economic growth through impacts on the agricultural and industrial sectors (Dell *et al.*, 2012). One proposed mechanism for this is the impact of heat stress on workers in the workplace (Dash and Kjellstrom, 2011). Temperature shocks negatively affect the growth of developing countries' exports, for which 1 degree Celsius of warming in a given year reduces the growth rate of its exports by 2.0-5.7% (Jones and Olken, 2010). The export sectors most affected are agricultural and light manufacturing exports. There is no detectable effect for higher income countries (Jones and Olken, 2010).

18.4.3.2. Energy Systems

Energy production and consumption is growing rapidly globally, with much of the growth taking place in low income and emerging economies. Due to the large number of non-climate confounders, the literature on detection and attribution for the energy sector is sparse. There is a significant literature identifying the climate sensitivity of various parts of the energy sector. Higher temperatures have been shown to raise the demand for cooling and lower the demand for heating. Cooling demand is largest in the summer and it has been shown for some areas that peak loads during the summer months have increased and that this peak is highly correlated with summer maximum temperatures (Franco and Sanstad, 2008). The literature showing the opposing effects of warmer winters and summers on electricity and gas demand using statistical methods have confirmed this U-shaped relationship of energy and electricity demand in temperature for the United States and elsewhere (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Deschênes and Greenstone, 2011).

Production losses from thermal power plants increase when temperatures exceed standard design criteria (e.g., Erdem and Sevilgen, 2006), as would be expected to occur more frequently under climate change. Power generation facilities may also experience performance losses and other impacts related to changes in access to and temperature of cooling water, as well as sea level rise and extreme weather events (Durmayaz and Sogut, 2006; CCSP, 2007; Kopytko and Perkins, 2011, see also 10.2). Further, solar photovoltaic cells become less efficient during hot days (Skoplaki and Palyvos, 2009).

The impacts of higher temperatures and extreme weather events on energy delivery, transmission and distribution vary across different empirical studies, facility characteristics, geographic regions, and other factors. Barges and ocean vessels that transport energy resources have been shown to be particularly vulnerable to hurricanes, storms, and flooding; pipeline performance can be affected by increasing ambient and soil temperatures, as well as extreme events (CCSP, 2007, see also 10.2). Some studies have quantified the general relationship between temperature and electricity transmission and distribution infrastructure, finding that increased temperatures can accelerate the aging of transformer insulation, lead to efficiency losses, and create power system reliability issues (Swift *et al.*, 2001; Li *et al.*, 2005; Askari *et al.*, 2009).

18.4.3.3. Tourism

Tourism is a climate sensitive economic sector and ample research has been performed to understand its sensitivity to climate change and impacts of (future) climate change on tourism, yet little to no literature has focused on detection and attribution of observed impacts (cf. Scott *et al.*, 2008, see also 10.6). A comparatively well-studied area is the climate sensitivity of wintersports in lower lying areas. For example, the increase in investment in artificial snow machines in the European Alps can be attributed with *high confidence* to a general decrease of snow depth, snow cover duration and snow fall days since the end of the 1980's for low-elevation mountain stations (Durand *et al.*, 2009; Valt and Cianfarra, 2010; Voigt *et al.*, 2011), which in turn has been attributed to anomalous

warm winter temperatures over the past 20 years (Marty, 2008). Increased variability in precipitation, shrinking glaciers and milder winters have been shown to negatively affect visitor numbers in winter sports areas in Europe and North America (Becken and Hay, 2007). Eijgelaar *et al*. (2010) argue that so-called "last chance tourism" is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. Farbotko (2010) uses a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. In contrast, Zeppel (2012) states a low level of concern for coral bleaching by tourists visiting the Great Barrier Reef.

18.4.4. Impacts of Extreme Weather Events

The impacts of extreme weather events depend on the frequency and intensity of the events, as well exposure and vulnerability. Climate change is expected to affect both the frequency and intensity of extreme weather events including extreme temperature, droughts, heavy rainfall, and tropical and extratropical cyclones (IPCC, 2012). There is *low to high* confidence that such changes have already occurred, depending on the type of extreme (WGI AR5 Chapter 10.6). However, the impacts of extreme weather events also depend on the vulnerability and exposure of systems. It is possible that climate change can affect vulnerability and exposure, but both can also be affected by non-climate confounders, most notably economic development.

18.4.4.1. Economic Losses due to Extreme Weather Events

Extreme weather events can have economic impacts arising from damage to private and public assets as well as the temporary disruption of economic activities. Although immediate economic impacts are most noticeable, long-term impacts are also possible, as are impacts beyond the area directly affected by the event. Some economic impacts are not readily monetizable and are thus excluded from most economic assessments (Handmer *et al*., 2012, their chapter 4.5.1, 4.5.3).

There is *high confidence* that economic costs of extreme weather events have increased over the period 1960-2000, with insured losses increasing more rapidly than overall losses (Handmer *et al*., 2012, their chapter 4.5.3.3, 4.5.4.1). This is also reflected by an increase in the frequency of extreme weather-related disasters over the same period (Neumayer and Barthel, 2011). Recent studies from Latin America (Mexico, Colombia, Peru) highlight both variability and positive trends in disaster frequency, (unadjusted) losses and other damage metrics (Saldaña-Zorrilla and Sandberg, 2009; Marulanda *et al*., 2010; Rodriguez-Oreggia *et al*., 2012; Huggel *et al*.). However, there is *high confidence* that the greatest contributor to increased cost is rising exposure associated with population growth and growing value of assets (Bouwer *et al*., 2007; Bouwer, 2011; Barthel and Neumayer, 2012; Handmer *et al*., 2012, their Chapter 4.2.2, Box 4.2 and 4.5.3.3).

To account for changes over time in the value of exposed assets, many studies attempt to normalize monetary losses by an overall measure of changes in asset value. Although there is considerable year-to-year variability associated with the occurrence of extreme weather events, most studies have found no detectable trend in normalized losses consistent with anthropogenic climate change. Studies of normalized insured losses, that in general meet higher data quality standards than data on overall losses due to thoroughly monitored payouts, have focused on developed countries including Australia, Germany, Spain, the US, Spain (Changnon, 2007; Changnon, 2008; Changnon, 2009a; Changnon, 2009b; Barredo *et al*., 2012; Barthel and Neumayer, 2012, see also 10.7.3; Sander *et al*., 2013), Studies of normalized losses from extreme winds associated with hurricanes in the US (Miller *et al*., 2008; Pielke Jr *et al*., 2008; Schmidt *et al*., 2010; Bouwer and Botzen, 2011) and the Caribbean (Pielke Jr *et al*., 2003), tornadoes in the US (Brooks and Doswell, 2002; Boruff *et al*., 2003; Simmons *et al*., 2012) and wind storms in Europe (Barredo, 2010) have failed to detect trends consistent with anthropogenic climate change, although some studies were able to find signals in loss records related to climate variability, such as century-scale damage and loss of life due to wildfires in Australia related to El Niño Southern Oscillation and Indian Ocean dipole phenomena (Crompton *et al*., 2010), or decadal-scale typhoon loss variablilty in the Western North Pacific (Welker and Faust, 2013).

Although there are a number of data issues that may limit the reliability of assessments of the economic impacts of extreme weather events (Crompton and McAneney, 2008; Bouwer and Botzen, 2011; Nicholls, 2011; Handmer *et*

al., 2012, their Chapter 4.5.3.3, see also 10.7.3), there is *limited evidence* of a trend in the economic impacts of extreme weather events that is consistent with a change driven by observed anthropogenic climate change.

18.4.4.2. Detection and Attribution of the Impacts of Single Extreme Weather Events to Climate Change

Although most studies of the relationship between climate change and extreme weather events have focused on changes over time in their frequency and intensity, a few studies have focused on the contribution of climate change to specific events (WGI AR5 Chapter 10.6.2). Assessing the contribution of climate change to a specific event poses particular challenges, both in terms of methodology and communication of results (Allen, 2011; Curry, 2011; Hulme *et al*., 2011; Trenberth, 2011). If climate change was among the drivers for a specific extreme weather event, there remains the question how this contribution translates into associated impacts and damages. Only a few studies have attempted to evaluate the role of climate change in the impacts of individual extreme weather events. Pall et al. (2011) and Kay et al. (2011), using observational constraints on climate and hydrologic model simulations, concluded that greenhouse gas emissions have increased the probability of occurrence of a comparable flooding event in autumn 2000 over the UK. A similar study for recent high flood years in the Okavango Delta, Botswana, found a decreased probability of high floods (Wolski *et al*., 2013). The autumn 2000 UK studies did not evaluate the relative role of other factors, however, while the Okavango study argued that the effects of land use, land cover, and water management change in the Okavango Basin were negligible.

In highly temperature-sensitive regions such as high mountains there is *high confidence* that several extreme impact events of the 20th and 21st century can be qualitatively attributed to effects of climate change, namely glacier lake outburst floods due to glacier recession and subsequent formation of unstable lakes (Evans and Clague, 1994; Carey, 2005; Bajracharya and Mool, 2009), debris flows from recently deglaciated areas, and rock fall and avalanches following the loss of mechanical support accompanying glacier retreat (Haeberli and Beniston, 1998; Oppikofer *et al*., 2008; Huggel *et al*., 2012b; Stoffel and Huggel, 2012, see also 18.3.1.3). Similar multiple-step approaches can be used to evaluate the contributions of anthropogenic emissions to recent damaging extreme events (see Table 18-4).

Irrespective of whether a specific event can be attributed in part to climate change, there is ample evidence of the severity of related impacts on people and various assets. Both low- and high-income countries have been strongly impacted by extreme weather events in recent years, but the impacts relative to economic strength have been higher in low-income countries (Handmer *et al*., 2012). Similarly, at the national scale, poor or elderly people have been disproportionately affected, as documented for Hurricane Katrina in the US in 2005 (Elliott and Pais, 2006; Bullard and Wright, 2010) or the 2003 European heat wave (Fouillet *et al*., 2008). Exacerbating effects of extreme weather events are mostly of non-climatic nature, including increasing exposure and urbanization, land-use changes including deforestation, or increasingly vulnerable infrastructure.

An illustrative case is the flood damage in New York City during the landfall of Hurricane Sandy in 2012. The storm surge hazard is expected to increase with rising local sea level as a result of anthropogenic emissions, notwithstanding any changes in associated meteorology (Lin *et al*., 2012). However, increased exposure of buildings, people, and infrastructure in New York City has probably contributed to a much larger increase in risk over the past century (Aerts *et al*., 2013). Against that increase, though, there has been a major investment in reducing vulnerability and increasing resilience, partly in response to past extreme events (Tollefson, 2013). Determining a contribution from anthropogenic climate change amongst such large competing factors, including diagnosing the forces behind adaptation, remains a major challenge.

[INSERT TABLE 18-4 HERE

Table 18-4: Illustrative selection of some recent extreme impact events for which the role of climate has been assessed in the literature. The table shows confidence assessments as to whether the associated meteorological events made a substantial contribution to the impact event, as well as confidence assessments of a contribution of anthropogenic emissions to the meteorological event. The assessment of confidence in the findings is not necessarily a conclusion of the listed literature but rather results from assessment of the literature. Assessment of the role of

anthropogenic emissions in the impact event requires a multi-step evaluation. Partly based on Coumou and Rahmstorf (2012).]

18.4.5. Human Health

IPCC AR4 (Confalonieri *et al*., 2007) concluded that there was *weak to moderate evidence* (with *low to medium confidence*) of climate change effects on three main categories of health exposures: vectors of human infectious diseases (changes in distribution), allergenic pollen (changes in phenology), and extreme heat exposures (trend in increased frequency of very hot days and heat wave events).

For pollen production, changes in phenology have been consistently observed in mid to high latitudes with, for example, earlier onset in Finland (e.g., Yli-Panula *et al*., 2009) and Spain (D'Amato *et al*., 2007; García-Mozo *et al*., 2010, see also 4.3). In North America, the pollen season of ragweed (*Ambrosia* spp.) has been extended by 13-27 days since 1995 at latitudes above 44°N (Ziska *et al*., 2011). Allergic sensitization of humans has changed over a 25 year period in Italy, but the attribution to observed warming remains unclear (Ariano *et al*., 2010).

The most direct potential health impact of climate change is through exposure to higher temperatures. The association between very hot days and increases in mortality in temperate populations is very robust but depends on factors such as geographic location, the age structure of the population, and the prevalence of air-conditioning (11.2.2). Seneviratne *et al*. (2012) concluded that there is *medium* to *high confidence* in detection of non-zero trends in increasing frequency of hot days and nights, decreasing frequency of cold days and nights, and in the duration of heat waves and warm spells over temperate subcontinental regions, and that on the global scale it is *likely* that anthropogenic emissions have had at least a minor role in these changes. However, the translation of this trend in hazard to a trend in exposure is complicated by evidence of changes in social, environmental, and behavioral factors (e.g., Carson *et al*., 2006).

Overall, Confalonieri *et al*. (2007) concluded that there was a lack of evidence for observed effects in human health outcomes, and this remains the case. Disease patterns change considerably over time due to changes in exposures (e.g. smoking patterns), control measures (vaccination, drug resistance), and population structures (population aging). Therefore, observations of trends in health outcomes provide little insight into a role of climate change. The detection of a climate-change-induced trend for any health outcome requires that changes in reporting over time need to be taken into account. Adaptation is an added confounding factor, as health agencies are mandated to intervene, and people are liable to alter exposures, as soon as risks are identified. With regard to temperature-related mortality, Christidis *et al*. (2010) examined the roles of changing exposure and health care and of anthropogenic climate change in observed trends in excess mortality during cool and warm days. They concluded that anthropogenic climate change had at most a minor role in trends in temperature-related mortality in England and Wales over the three decades, relative to a major role for the combined trends of exposure and health care; however, assessment of the existence of a minor role for anthropogenic climate change may have been sensitive to the lack of interseasonal mortality relationships in their modeling setup (Rocklöv *et al*., 2009; Ha *et al*., 2011).

There is *limited evidence* regarding the role of observed warming in changes in tick-borne disease in mid to high latitudes. The upsurge of tick borne encephalitis (TBE) in the 1980-90s in central and Eastern Europe has been attributed to socio-economic factors (human behavior) rather than temperature (Šumilo *et al*., 2008; Šumilo *et al*., 2009). Changes in the observed incidence of TBE in central Sweden remain unexplained however (Randolph, 2010). Changes in the latitudinal and altitudinal distribution of ticks in Europe are consistent with observed warming trends (e.g., Gray *et al*., 2009), but there is no evidence so far of any associated changes in the distribution of human cases of tick-borne diseases. In North America, a northward expansion of the distribution of the tick vector (*Ixodes scapularis*) was observed in the period 1996 to 2004 (Ogden *et al*., 2010).

There is *limited evidence* of a change in the distribution of rodent-borne infections in the US (plague and tularaemia) consistent with observed warming (Nakazawa *et al*., 2007). Specifically, a northward shift of the southern edge of the distributions of the diseases (based on human case data for period 1965-2003) was observed. There was no change detected in the northern edge of the distributions though.

Malaria incidence has been monitored in the Kericho region of Kenya for over three decades, with a trend toward increasing incidence in the late 1990s. A local warming trend also occurred during the end of the observation period (Omumbo *et al*., 2011). Other studies have confirmed that malaria incidence is sensitive to temperature and rainfall effects in nonlinear ways, but it is a complex ecological system, with changes in vector, human and parasite behavior that need to be considered. A mosquito-human model, however, has shown that predicted malaria cases exhibit a strongly non-linear response to observed warming (Alonso *et al*., 2011). A detailed review by Chaves and Koenraadt (2010) concludes that there is *robust evidence* that decadal temperature changes have played at least a minor role in the malarial trends of the East African highlands, arguing that it may the combination of many factors that has been crucial. However, temperature trends should nonetheless not be considered the main or sole cause of such changes in malaria in the east African highland region, and globally the dominant trend has been a contraction of the geographical range of malaria and a decrease in malaria endemicity over the past century (Gething *et al*., 2010).

18.4.6. Human Security

18.4.6.1. Violent Conflicts and Social Disruptions

A small number of studies have examined the connection between the collapse of civilizations and large-scale climate disruptions like severe or prolonged drought. DeMenocal (2001) summarized the evidence for a number of cases. However, attribution to climate change can be made with only *low confidence* due to limitations on both historical understanding and data. Similarly, a small number of studies have suggested that levels of warfare in Europe and Asia were relatively high during the Little Ice Age (Parker, 2008; Brook, 2010; Tol and Wagner, 2010; White, 2011; Zhang *et al*., 2011), but again attribution to climate can only be made with *low confidence*. There is no evidence of a climate effect on inter-state conflict in the post-WWII period.

Most of the recent research in this area has focused on the relationship between climate variability – as opposed to climate change – and civil conflict, with most studies focusing on Africa. Although some studies have established statistical relationships (Miguel *et al*., 2004; Hendrix and Glaser, 2007; Burke *et al*., 2009; Hsiang *et al*., 2011), their results have been questioned (Buhaug *et al*., 2010; Buhaug and Theisen, 2012; Slettebak, 2012; Theisen *et al*., 2012) and no consensus has been reached. Both the detection of a climate effect on civil conflict and its attribution to climate change can be made with only *low confidence*.

Very recent work has begun to examine links between climate variability and small-scale communal violence (Adano *et al*., 2012; Butler and Gates, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012), but it is too early attach anything but *low confidence* to the detection of a climate effect and its attribution to climate change.

Finally, a number of efforts have been made to establish a link between violent crime and high temperatures (Anderson, 1987; Field, 1992; Anderson, 2001; Rotton and Cohn, 2001; Butke and Sheridan, 2010; Breetzke and Cohn, 2012; Gamble and Hess, 2012). However, the findings remain controversial with most studies identifying other factors as explaining variations in rates of violent crime (Kawachi *et al*., 1999; Fajnzylber *et al*., 2002; Neumayer, 2003; Cole and Gramajo, 2009) and the detection of a temperature effect on violent crime and its attribution to climate change can be made only with *low confidence*.

18.4.6.2. Migration

Large population movements, in response to climatic events, are sometimes considered a human security issue. Empirical detection of such relationships has been slow because data sets on population movements are not yet well developed. Moreover, the attribution of migration to climate change is difficult because economic, political, social, demographic, and other environmental drivers interact with climatic drivers to influence migration (Black *et al*., 2011). Few studies measure or empirically demonstrate how rainfall or temperature changes cause a strengthening

or weakening of the various forces driving migration, especially income levels and income variability (Lilleør and van den Broeck, 2011).

Some large sample studies have been able to detect population movements in response to natural disasters (Smith *et al*., 2006b; Boustan *et al*., 2012) and climate-induced agricultural losses (Feng *et al*., 2012) in the United States, where data quality is high. In both the United States and African contexts, crop losses have also been associated with rural to urban population movements within a country (Barrios *et al*., 2006; Feng *et al*., 2012). By statistical attribution, Marchiori *et al*. (2012) estimate that anomalous temperature and rainfall have displaced roughly 128,000 people per year in Sub-Saharan Africa during 1960–2000.

Drought has prompted both short-distance (Tacoli, 2009) and long distance international migration, with the Mexican drought of the 1990s providing an example of the latter (Saldaña-Zorrilla and Sandberg, 2009; Feng *et al*., 2010). In Burkina Faso, temporary moves to other rural areas have increased as a result of a reduction in rainfall (Henry *et al*., 2004). Even though there is a statistically significant relationship between migration outcomes and rainfall variability, Kniveton et al. (2011) report from own fieldwork that only 27 of 3,517 households identified rainfall as a driver of migration.

18.4.7. Rural Areas, Livelihoods and Poverty

Much like for the other sectors discussed above, available research about climate related impacts on livelihood and poverty distinguishes between climate sensitivity and impacts driven by climate change (e.g. gradual temperature changes, and changes in climate variability). A climate sensitivity of livelihoods has been observed with *high confidence*, while there is a paucity of evidence about impacts of gradual climate change on livelihoods and poverty. Detection of changes in livelihood aspects is often difficult due to a lack of data. If trends are actually detected, many confounding factors contribute to detected changes. Because of the important confounders and the current limitations in attributing climate extremes and changes in variability to climate change (see 18.4.4.2), confidence in attribution of changes in livelihoods and poverty to climate change is typically *low* or *very low* (Nielsen and Reenberg, 2010).

Primarily negative impacts from historical climate variability and extremes, and to a much lesser degree from climate change, have been observed on people's natural, physical, economic, social and cultural assets (see Table 18-5). Impacted natural assets include land, water, fish stocks and livestocks (Osbahr *et al*., 2008; Bunce *et al*., 2010). There is growing concern about negative effects of climate change and ocean acidification on marine and coastal fisheries, and the livelihoods of fisherfolks (Cooley and Doney, 2009; Badjeck *et al*., 2010), however there is no literature available discussing observed impacts.

[INSERT TABLE 18-5 HERE
Table 18-5: Cases of regional livelihood impacts attributable with varying degree to weather- and climate related events, climate change or climate variability.]

Natural and physical assets (e.g. settlements) of many poor people have been affected by weather- and climate-related extreme events. Poor people living in hazard exposed areas in Africa and Latin America were affected by floods and landslides in the 1990's and 2000's with some upward trend mainly due to increased urbanization (*low to medium confidence* for increasing floods and landslides, *high confidence* for increasing number of people affected) (Douglas *et al*., 2008; Hardoy and Pandiella, 2009). Although there is evidence of a decline in average precipitation in West Africa since 1960 (Lacombe *et al*., 2012) including repeated droughts (Dietz *et al*., 2004; Armah *et al*., 2011), which in some cases has been partly attributed to anthropogenic climate forcing (Jenkins *et al*., 2005; Biasutti and Giannini, 2006), there is *limited evidence* of changes in poverty among affected small-holder and subsistence farmers that can be attributed to climate drivers such as rainfall decline and droughts.

In rural areas correlations have been found between climatic variability and extreme events and livelihood diversification in West Africa (Nielsen and Reenberg, 2010) and Mexico (Eakin, 2006) and in Mexico frequent

impacts of natural disasters correlate with substantial income drops, marginalized, grain-intensive farming and low access to credit (Saldaña-Zorrilla and Sandberg, 2009).

Climate impacts disproportionately affect poor populations, thus increasing social and economic inequalities, both in urban and rural areas, and in low-, middle- and high-income countries. Climatic factors thereby interact with aspects of race, class, gender, ethnicity or age (Nightingale, 2011). Evidence for poor people in high income nations being disproportionately affected by weather- and climate related extreme events comes, for instance, from 2005 US Hurricane Katrina (Elliott and Pais, 2006; Bullard and Wright, 2010) or drought events in Australia (Alston, 2011). Glacial lake outburst floods in the Peruvian Andes also affect different populations depending on their degree of exposure, level of vulnerability, race, ethnicity, and socio-economic class (Carey, 2010; Carey *et al.*, 2012b). There has been an observed gender bias in impacts from climate variability and extremes, due to gender specific roles within the household, communities, and wider socio-political and institutional networks (Carr, 2008; Arora-Jonsson, 2011, see also Box 13-1).

For indigenous peoples, specific rights, including the right to life, adequate food, water, health, adequate housing, and the right to self-determination, are directly implicated by the impacts of climate change and variability (Ford, 2009b, see also Box 18-5). Livelihoods of indigenous people in the Arctic have been identified as among the most severely affected by both climate change and variability, including food security aspects, traditional travel and hunting, and cultural values and references (Beaumier and Ford, 2010; Pearce *et al.*, 2010). Negative effects on social and cultural assets by climatic and non-climatic stressors have also been identified in Africa with respect to social networks of the poorest, elderly and female-headed households (Osbahr *et al.*, 2008). Impacts of rising temperatures and increased variability of weather extremes on crops and livestock of indigenous people in highlands were furthermore reported from Tibet (Byg and Salick, 2009) and the Andes of Bolivia (McDowell and Hess, 2012). Shifts from transient to chronic poverty due to climate change and variability are suggested for livelihoods and households that, unlike more affluent ones, lack appropriate response to, and ability to cope with altered seasonalities, unpredictable seasons, and extreme events such as floods and droughts (Hardoy and Pandiella, 2009).

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Box 18-5. Detection, Attribution, and Traditional Ecological Knowledge (TEK)

Indigenous and local peoples often possess detailed knowledge of climate change that is derived from observations of environmental conditions over many generations. Consequently, there is increasing interest in merging this traditional ecological knowledge (TEK)—also referred to as indigenous ecological knowledge (IEK) or simply indigenous knowledge (IK)—with the natural and social sciences in order to better understand and detect climate change impacts (Huntington *et al.*, 2004; Parry *et al.*, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Ford *et al.*, 2011; Diemberger *et al.*, 2012). TEK, however, does not simply augment the sciences, but rather stands on its own as a valued knowledge system that can, together with or independently of the natural sciences, produce useful knowledge for climate change detection or adaptation (Agrawal, 1995; Cruikshank, 2001; Hulme, 2008; Berkes, 2009; Byg and Salick, 2009; Maclean and Cullen, 2009; Wohling, 2009; Ford *et al.*, 2011; Herman-Mercer *et al.*, 2011).

Cases in which TEK and scientific studies both detect the same phenomenon offer a higher level of confidence about climate change impacts and environmental change and the value of indigenous knowledge (Huntington *et al.*, 2004; Laidler, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Gamble *et al.*, 2010; Green and Raygorodetsky, 2010; Alexander *et al.*, 2011; Cullen-Unsworth *et al.*, 2011). For example, in Peru's Cordillera Blanca mountains, local residents and instrument-based scientific analysis both report increasingly rapid glacial recession, less snow in the upper watershed, decreased water supplies in glacier-fed basins, and an increase of falling glacier “blocks” since the latter half of the 20th century (Bury *et al.*, 2010; Carey, 2010; Baraer *et al.*, 2012; Carey *et al.*, 2012b). For another, in Tibet, many, but certainly not all, local residents observed warming temperatures, less snow, and shrinking glaciers, which are consistent with scientific interpretations (Byg and Salick, 2009). At Clyde River, Nunavut, Canada, Inuit and scientific observations have detected that wind speed has increased in recent years and that wind direction changes more often over short periods (within a day) than it did during past decades (Gearheard *et al.*, 2010). Finally, in the Canadian Arctic, Inuit sea ice experts and scientists have

both observed the thinning of multiyear sea ice, the shortening of the sea ice season, and the declining extent of sea ice cover, with Inuit observers reporting less predictability in the sea ice and more hazardous travel and hunting at ice edges (Nichols *et al*., 2004; Laidler, 2006; Krupnik and Ray, 2007; Ford *et al*., 2009; Aporta *et al*., 2011).

TEK can also inspire scientists to study new issues in the detection of climate change impacts. In one case, experienced Inuit weather forecasters in Baker Lake, Nunavut, Canada, reported that it had become increasingly difficult for them to predict weather, suggesting an increase of weather variability and anomalies in recent years. To test Inuit observations, scientists analyzing hourly temperature data over a 50 year period confirmed that afternoon temperatures fluctuated much more during springtime during the last 20 years—precisely when Inuit forecasters noted unpredictability—than they had during the previous 30 years (Weatherhead *et al*., 2010).

Despite frequent confluence between TEK and scientific observations, there are sometimes discrepancies between them. These discrepancies indicate uncertainty in the identification of climate change impacts. Attribution of impacts to anthropogenic climate change, for example, tends to have much less convergence between TEK and the natural sciences. While community members in Canada's Northwest Territories report that less ice cracking during the last decade was a result of winter warming caused by climate change, scientists have concluded that the relationship between ice cracking and air temperature is much more complex and requires more research on water temperature, ice thickness, snow cover, and ice properties in order to attribute reduced ice cracking to global climate change (Woo *et al*., 2007).

Scale is another problem in the detection of climate change: TEK and scientific studies frequently focus on different and distinct scales that make comparison difficult. Local knowledge may fail to detect regional environmental changes while scientific regional or global scale analyses may miss local variation (Wohling, 2009; Gamble *et al*., 2010). In some cases TEK and scientific studies measure or note distinct phenomenon that cannot be compared or have inaccuracies (Gearheard *et al*., 2010). Furthermore, TEK based observations and related interpretations necessarily need to be viewed within the context of the respective cultural, social, and political backgrounds (Agrawal, 1995). Therefore, a direct translation of TEK into a western science perspective is often not feasible.

_____ END BOX 18-5 HERE _____

18.5. Detection and Attribution of Observed Climate Impacts across Regions

Since the AR4, significant new knowledge about detected impacts of recent climate change has been gained from all continents of the world, assessed in the regional chapters 22-29 of this report (for relevant information on Ocean regions from Chapter 30, see 18.3.2). The following sections provide a short overview about key findings for each of the eight world regions discussed in Chapters 22-29, along with a summary of relevant recent observed climate change. Further details of regional detection and attribution findings are summarized in 18.5.9 for various collections of natural, managed, and human systems.

18.5.1. Africa

For much of Africa, knowledge about recent climate change is limited, due to weak climate monitoring, and gaps in coverage continue to exist. On the other hand, the low natural temperature variability over the continent allows earlier detection of warming signals. Thus there is *medium to high confidence* in regional warming, with *low to high confidence* in attribution to anthropogenic emissions. A main regional feature has been the drying of the Sahel during the decades following 1970, but that trend has halted during the most recent decade (see also 22.2).

African environmental systems present many strong challenges for the potential detection and attribution of responses to climate change. Given the weak spatial and temporal variations in temperature, there is smaller scope for migrational and phenological responses to anthropogenic climate change than in other parts of the world. Furthermore, high quality monitoring is relatively sparse in time and space, and is often unsuitable for detecting changes across margins and borders where responses to climate change are most expected. The dearth of studies

examining attribution questions means it is currently difficult to estimate the degree to which studies are selectively published based on results, and thus to determine whether each attribution study is only indicative of local reasons for concern or if it is more generally representative of a broader domain.

Since the AR4 there has been a particular research focus on three geographic domains: the effects of dryness in the Sahel since 1970 on tree density; the effects of surface warming and resulting increased stratification on the Great Lakes on the lake ecology; and the effect of warming on species ranges in southern Africa, where spatial temperature gradients are larger and there is more scope for range shifts as a measureable response.

18.5.2. Europe

Amongst all continents, Europe has the longest tradition in climate monitoring. Warming has been occurring across the continent in all seasons, with an associated decreasing frequency of cold extremes and increasing frequency of hot extremes (Seneviratne *et al.*, 2012). The Southern parts of the continent (the Mediterranean) have been getting drier, while northern areas have been getting wetter (23.2.2.1), with a general increase in the frequency of extreme wet events everywhere (Seneviratne *et al.*, 2012).

Significant warming-related impacts have long been observed in Northern and Central Europe, with substantial loss of Alpine glaciers, longer growing seasons, associated productivity increases and changed phenology of many plant and animal species on land as well as in the Atlantic Ocean. Higher temperatures and generally drier conditions have likely contributed to the stagnation of agricultural yields that would otherwise have been expected to increase as a consequence of improved agricultural practices and higher atmospheric CO_2. In the Mediterranean drier and hotter conditions have contributed to increased wildfires.

18.5.3. Asia

Asia spans a wide range of climate types and expected climate changes, but warming has been observed throughout the continent with northern areas amongst the fastest warming on the planet. Precipitation trends vary geographically, with a more frequent but weaker Indian monsoon (WGI AR5 Chapter 14.7.10), and contrasting increasing and drying trends over coastal and inland China (24.3.1).

Among the most wide-spread observed impacts of recent climate change in Asia are the degradation of permafrost occurring throughout its current distribution in Siberia, Central Asia and on the Tibetan Plateau, matching observations from elsewhere in the world and to a very high degree explained by warming. Substantial new evidence has been collected since AR4 on glaciers in Asia. Across most of Asia glaciers have been shrinking, except from some areas in the Karakorum and Pamir. In some rivers (e.g. in China) an increase in runoff was observed in glaciated catchments.

Plants and animals are changing their phenology and growth in many parts of Asia, largely due to climate change, many species are also shifting their distribution northwards or upwards in elevation. In the oceans of tropical Asia and around Japan, coral reefs and large seaweeds are in decline.

18.5.4. Australasia

There is *very high confidence* of warming over Australian and New Zealand during the past century, and *high confidence* in hot extremes becoming more frequent and cold extremes becoming less frequent (25.2, Table 25-1). Winters in southern areas of Australia have become drier in the past few decades and the northwest has become wetter, and precipitation increased over the south and west of both islands of New Zealand (*high confidence*). While there have been no significant trends in drought frequency over Australia, regional warming may have increased their hydrological intensity (*low confidence*, Table 25-1).

There is *high confidence* of a significant decline in late season snow depth several sites in Australia's Snowy Mountains, and a decline of glacier volume by 25% in New Zealand since the middle of the 20th century (table 25-1). In many Australian terrestrial ecosystems, some observed changes in the distributions, genetics, phenology of individual species, and in the structure and composition of some ecological communities can be attributed to recent climatic and atmospheric trends, but non-climatic drivers, such as changes in fire management, grazing and land-use, also play a significant role. The 1997-2009 drought has affected freshwater systems in the eastern states and the Murray Darling Basin, but for many freshwater systems, direct climate impacts are difficult to detect. In New Zealand, few changes in ecosystems have been attributed to climate change.

Climate change impacts have been profound in marine systems around Australia and New Zealand, involving large latitudinal shifts of climatic zones and associated biota. Many of these changes have been associated with ocean warming, although for others the impacts of interacting non-climate stresses, including habitat degradation, coastal pollution and fisheries are also significant. About 10% of the observed 50% decline in coral cover on the Great Barrier Reef has been attributed to bleaching, the remainder to cyclones and predators.

Exceptional heatwave conditions in Australia have been associated with substantial increases in excess deaths and heat-related hospital admissions (Khalaj *et al*., 2010; Loughnan *et al*., 2010).

18.5.5. North America

North America spans a wide range of climate types and observed climate changes. While the northwest of the continent has been amongst the fastest warming on the planet, the southeast of the USA has experienced slight cooling (26.2.2). Hot extremes have been becoming more frequent while cold extremes and frost days have been becoming less frequent over the past several decades. Trends in precipitation over western parts of the continent are strongly influenced by the variability of the El Niño/Southern Oscillation, with a matching drying and decreasing snowpack. The intensity of precipitation events has been increasing over most of the continent, but trends in dryness are spatially heterogeneous (26.2.2). There is *robust evidence* of an increase in intense tropical storms in the North Atlantic over the past several decades (WGI AR5 Chapter 2.6.3).

There is evidence for hydrological change in many parts of North America, particularly in catchments that are dominated by snowpack and ice. Terrestrial ecosystems have responded to warming with range shifts (upwards and polewards), changed phenology, productivity and mortality (insect outbreaks). In some regions, wildfires have become more frequent. Marine ecosystems significantly shift ranges northwards. Agricultural production is affected by increased drought conditions in the Southern US and Mexico. There is some evidence for infrastructural damage from more frequent climatic extremes.

18.5.6. Central and South America

Most of South America has been observed to be warming over the past half century, except for an observed cooling over a western coastal strip (27.2.1.1). Precipitation over much of Central and South America is strongly influenced by the El Niño/Southern Oscillation, with accompanying long-term variability. There has been in reduction in the number of dry summer months in the southern half of the continent, while observed trends over the Amazon are sensitive to the selection of time period (27.2.1.1).

Among the observed impacts of climate change in South and Central America there are some that stand with *high* or *very high confidence* in detection and attribution. These are: the retreat of tropical glaciers and ice-fields in the Andes, decreasing river flows in the western tropical Andes, increased streamflow in the La Plata basin and bleaching of coral reefs in the western Caribbean. Several impacts are associated to many confounding causes and although detection of change may be found with *high* levels of *confidence*, the confidence in attribution is *low* or *very low*. In this category are included the degrading and receding of the Amazon rainforest, mangrove degradation on the Northern coast of South America and the expansion of agricultural areas in climatically marginal regions of Argentina. With *high confidence* in detection and *medium confidence* in attribution, denoting perhaps an impact

more sensitive to climate than in the previous case, are included the increase in agricultural yields in Southeastern South America and the increase in frequency and extension of dengue fever, yellow fever and malaria.

Although the number of articles in the literature and of consolidated datasets has both increased in Central and South America during the past decade, still there are many gaps to be filled in mainly in remote regions and regarding historic temporal coverage.

18.5.7. Polar Regions

The areas of largest observed warming are all polar: the northwest of North America, northern Asia, and the Antarctic Peninsula. While this occurs against a large background of natural variability, WGI AR5 Chapter 10 conclude that it is *likely* that there has been an anthropogenic contribution to Arctic warming; for the Antarctic, however, there is *low confidence* in attribution due a sparse monitoring network, an apparent lack of warming in the continental interior, and the contrasting effects of greenhouse gas emissions and stratospheric ozone depletion (10.3.1.1.4). The nature of polar regions means that warming can lead to large changes in other aspects of the climate system, in particular the observed decrease in summer sea ice cover, earlier thaw, earlier spring runoff, and melting of permafrost (28.2).

Recent changes in the Arctic tundra hydrology are attributed to permafrost degradation caused by increasing air temperature and reduced albedo. Swamp formation, lake drainage, and ecosystem shifts are among the observed consequences. Permafrost degradation also affects traditional living for local and indigenous communities.

The ongoing reduction of sea ice cover and duration has profound impacts on the subsistence of many species in the Arctic as well as the Antarctic. Polar bears are suffering from reduced vigor and reproduction, and arctic seabird populations are facing longer flight distances for provisioning of their offspring due to phenological mismatch, resulting in decreasing reproductive success. Antarctic penguin species show decreasing numbers, attributed to shrinking stock of their main prey, the Antarctic krill, which in turn is affected by sea ice loss.

Changing snow conditions affect arctic plants and animals in various ways. Mild spells in the winter, with increasing frequency of rain on snow events and the formation of ice crusts in the snow pack has affected the populations and cyclicity of arctic grazers (voles, ptarmigans, reindeer and caribou) with cascading effects on their predators, e.g., the Arctic fox: Decreasing range of snow-beds in the Arctic summer have strong impacts on animal communities and reindeer husbandry.

The most easily detected change in the physiognomy of the arctic tundra is the ongoing increase in shrub cover as seen in many studies from the North American as well as the Eurasian Low Arctic and Subarctic, attributed to increasing temperature. In the Antarctic Peninsula, the two resident species of vascular plants have passed a summer temperature threshold, and the attribution of the observed sudden increase in production of mature seeds is not confounded by other drivers.

18.5.8. Small Islands

Despite the widely accepted high vulnerability of many small islands to climate change, including their close relationship with Coral Reefs, there are only few formal studies on observed impacts. Detection of climate change impacts in small islands is challenging due to the strong presence of other anthropogenic drivers of local environmental change. Attribution is further challenged by the strong influence of natural variability compared to incremental changes of climate drivers, and the lack of long term monitoring, high quality data.

Observations of impacts of sea level rise on small islands are scarce. In many cases phenomena which are associated with expected impacts of sea level rise such as erosion, inundation, wave overwash are also strongly linked with on-going, known climate variability and extremes and cyclic processes such as ENSO, storms and extreme tidal

phenomena. It is therefore difficult to quantify the degree to which such impacts can be attributed to climate change and sea level rise.

For example, there is evidence for higher than average sea level rise, with rates up to four times the global average (approximately 12 mm yr^{-1} between 1993 and 2009), in the tropical western Pacific region, where a large number of small island and atoll communities are located (Becker *et al.*, 2012; Meyssignac and Cazenave, 2012). However, these changes may be transient, caused by strong and persistent La Nina like conditions superimposed over sea-level rise and are therefore currently not unambiguously attributed to climate change (Becker *et al.*, 2012).

18.5.9. Impacts across Regions

In order to allow for comparison between the various regions of the world, the following synopsis regroups the main conclusions for various components of the physical, biological, and human systems. The regional synopses is divided into various systems, covering observed impacts of regional climate change for: snow, ice and mountains, rivers and lakes (Table 18-6); terrestrial ecosystems, droughts and wildfires (Table 18-7); marine ecosystems and coastal processes (Table 18-8); and human and managed systems such as food production, economic impacts, and health (Table 18-9). These assessments follow from discussions in the various sectoral and regional chapters of this report and in earlier sections of this chapter.

Broadly, there is now at least *robust evidence* for observed impacts in most of the categories of physical and biological systems listed in most of the regions. There is also evidence of observed impacts on food production in many of the regions, while detection of impacts in other human systems remains limited. Further interpretation of these regional synopses within the "Reasons for Concern" framework forms the basis of the synthesis assessment of 18.6.

[INSERT TABLE 18-6 HERE
Table 18-6: Observed impacts of climate change on snow, ice and mountains, and rivers and lakes, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

[INSERT TABLE 18-7 HERE
Table 18-7: Observed impacts of climate change on terrestrial ecosystems, and occurrence of Drought and Wildfire, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

[INSERT TABLE 18-8 HERE
Table 18-8: Observed impacts of climate change on Marine and marine influenced Ecosystems, and Coastal processes, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

[INSERT TABLE 18-9 HERE
Table 18-9: Observed impacts of climate change on Human Systems across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.]

18.6. Synthesis: Detected Impacts of Climate Change and Reasons for Concern

18.6.1. Approach and History

A key motivation for the effort in assessing observed changes is the possibility that observed impacts could constitute indications of future expected changes. Observed losses in glacial volume, for example, lend additional plausibility to model-based expectations that additional warming could result in additional ice loss. Due to the

complex nonlinear behavior of most environmental systems, it cannot always be assumed that past impacts scale linearly to future impacts. Likewise, absence of past impacts cannot constitute evidence against the possibility of future impacts. Nonetheless, detection and attribution of observed impacts may serve as part of the foundation for a climatic risk analysis. In order to do so, the total body of observed impacts needs to undergo a synthetic analysis pointing towards the conceivable risks.

The AR4 precursor of the current chapter (Rosenzweig *et al*., 2007) organized its efforts around a geographically distributed empirical analysis of correlation across numerous detailed and localized studies of changing systems as described in Rosenzweig *et al*. (2008). Rather than expand that approach using the quickly growing scientific literature, the goal for this synthesis is to organize findings on detection and attribution in a way that fully covers the disciplinary, sectoral and geographic diversity of observed impacts. The approach aims to establish current conditions concerning the risk analysis model formulated earlier by the IPCC through the establishment of a limited number of "Reasons for Concern" (RFC). The RFC concept was developed in IPCC-TAR (Smith *et al*., 2001), adopted for a second time in IPCC-AR4 (IPCC, 2007a), and updated in Smith *et al*. (2009). The RFCs respond directly to requests from countries that the IPCC assesses the science with respect to the United Nations Framework Convention on Climate Change's (UNFCCC) commitment to "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992), without being policy prescriptive in terms of the definition of "dangerous". For the present synthesis, the goal is not to determine the levels of warming that correspond to a particular level of impact (as done in, e.g., IPCC, 2007b, Figure SPM.2); instead this analysis seeks to establish, qualitatively, the importance of impacts already observed in relation to the critical levels for concern indicated by the red colour of each bar portrayed in IPCC (2007a), using the levels revised by Smith *et al*. (2009).

While the summary of observed impacts, taken for themselves, cannot constitute an assessment of a probability-based measure of risk for dangerous anthropogenic interference, the degree to which the earlier projected impacts now have occurred can be useful for policy-relevant conclusions about the risks (chapters 1, 19). The actual quantification of risk for a given aspect of dangerous interference depends on the metrics chosen for the societal importance of a given impact and is not part of this analysis. Instead, the degree of concern is expressed in qualitative terms only, with an assessment of confidence in the assessment using standard IPCC terminology (Mastrandrea *et al*., 2010, 18.2). This is thought to directly support the development of policy-relevant conclusions about the risks expressed by each RFC.

As described more fully in Chapter 1 and earlier documentation, the five RFCs are (1) "Risks to Unique and Threatened Systems", (2) "Risks of Extreme Weather Events", (3) "Distribution of Impacts", (4) "Aggregate Impacts", and (5) "Risks of Large-Scale Discontinuities". Their broad definitions imply significant overlap, hence some observed impacts are referred to under more than one RFC. For consistency with the earlier assessments, the definitions and naming conventions in Smith *et al*. (2009) were nevertheless followed as rigorously as possible.

18.6.2. Five Reasons for Concern

18.6.2.1. Risks to Unique and Threatened Systems

The RFC of "Risks to Unique and Threatened Systems" is concerned with the potential for increased damage to, or irreversible loss of, plant and animal species, physical systems, and human livelihoods which are known to be highly sensitive to temporal and/or spatial variations in climate. Figure 18-4 displays current evidence derived from detection and attribution studies concerning observed impacts to unique and threatened systems as a result of observed changes in climate. Changes in the three indicated physical systems have at least *high confidence* in detection and at least *medium confidence* in attribution, with regional assessments also tending to have *high confidence*. There is at least *medium confidence* in both detection and attribution for at least one each of ecosystems, physical systems, and human systems, indicating observational evidence for moderate to strong reasons for concern for all three classes.

[INSERT FIGURE 18-4 HERE
Figure 18-4: Confidence in detection and attribution of observed impacts on unique and threatened systems as a result of recent climate change. Assessments are for confidence in detection of a change and for confidence in attribution of a major role of observed climate change. Large letters denote conclusions for the full-scale system, while small letters denote conclusions for regional subsets of the systems. System changes include shrinking / receding glaciers, mountain and lowland permafrost degradation, Arctic coastal permafrost degradation, increased mortality and bleaching of warm water reef-building corals, increased shrub cover and permafrost decay in the northern tundra, increased tree mortality in the Amazon, increased tree mortality in boreal forests, changes in Arctic marine ecosystems, decline in extent of mangroves and coastal wetlands, and impacts on livelihoods of indigenous Arctic peoples. See Table 18-10 for details and references.]

The systems with strongest detection and attribution evidence cover the Arctic, warm-water coral reefs, and mountains. In the Arctic, there is at least *medium confidence* of impacts on glaciers, permafrost, the tundra, marine ecosystems, and livelihoods of indigenous peoples, reflecting macroscopic changes across both natural and human systems and across the physical and ecological subregions. Evidence for the detection and attribution of shrinkage and recession of glaciers comes from all continents, while evidence for attribution of coral bleaching spans a similarly broad area of the tropical oceans (see Table 18-10). These observed impacts confirm the reason for concern about risks to unique and threatened systems.

[INSERT TABLE 18-10 HERE
Table 18-10: Reported confidence of detection of observed changes in "Unique and Threatened Systems" and attribution of observed changes to observed climate change. Assessments are for global or the indicated regional domain, with regional variations indicated in the final column.]

18.6.2.2. Risk of Extreme Weather Events

"This RFC tracks increases in extreme events with substantial consequences for societies and natural systems. Examples include increase in the frequency, intensity, or consequences of heat waves, floods, droughts, wildfires, or tropical cyclones" (Smith *et al.*, 2009). The risk of impacts by an extreme weather event is a combination of the probability of an extreme weather hazard and the consequences of the realization of that hazard. Hence, a change in the risk of impacts of extreme weather events could be caused by a change in the probability, intensity, or sequencing of the weather event itself (which are manifestations of recent climate change), or by a change in exposure, vulnerability, or the resilience of the impacted system. It follows that assessments of change in risk to anthropogenic climate change are particularly influenced by new evidence concerning the dominant drivers of change, whether climate change is one of those major drivers or not.

In the TAR, WGII found itself unable to detect a climatic component in the causal analysis of the increasing losses from extreme weather events, but outlined instead the significant vulnerabilities that could be expected if extreme weather events would increase with future climate change (IPCC, 2001, Technical Summary). In the AR4, detection and attribution was reported in terms of likelihood and supported in terms of consequence, with the conclusion that "It is now more likely than not that human activity has contributed to observed increases in heat waves, intense precipitation events, and the intensity of tropical cyclones. There are, as well, more observations of climate change impacts from extremes than in the TAR. Responses to some recent extreme climate events have also revealed higher levels of vulnerability across the globe, producing significant loss of life and property damage in both developing and developed countries" (IPCC, 2007b).

The current assessment confirms that, in many human systems, combined changes in exposure, vulnerability, and resilience have dominated past trends in risk. For instance, while there is *high confidence* that monetary losses related to extreme weather events have increased over the past 3-4 decades (ISDR, 2009, 10.7.3, 18.4.2), it is generally accepted that climate change has not been a major driver of that change in risk: instead, trends in exposure, wealth, and vulnerability of human systems have been the major factors for the increase in losses (IPCC, 2012, 10.7.3, 18.4.2). There has been considerable recent research and assessment into various components of the overall chain involved in extreme weather risk. Table 18-11 summarizes some notable new evidence concerning changes in

hazard and damage associated with extreme weather events that has been reported in the SREX, the WGI contribution to the AR5, and throughout this WGII contribution to the AR5.

[INSERT TABLES 18-11a AND 18-11b HERE
Table 18-11a: Confidence in detection of changes in extreme weather hazard and attribution of a major role of changing greenhouse gas concentrations in the observed changes.
Table 18-11b: Confidence in detection of observed trends in damage in various systems and attribution of a major role of observed changes in extreme weather to those observed trends.]

With regard to extreme weather hazard, temperature extremes have changed in many regions as a consequence of climate change (*high confidence*), with lower confidence in weather extremes that are less directly related to temperature or that occur on smaller spatial and time scales (where the connection with global mean temperature is less secure) (Seneviratne *et al*., 2012, WGI AR5 Chapter 10.6.1). Given the documented sensitivity of many systems to hot temperatures, the increase in extreme heat hazard implies a significant reason for concern. Indeed, for some systems there is evidence that local trends in temperature extremes have had a direct impact (Table 18-11b). There is also evidence that other trends in extreme weather hazard which are closely tied to global or regional warming, such as hazards related to sea level rise or sea ice retreat, have also been leading to increased damage.

Most of the evidence of attributable changes in impact risk due to weather extremes concerns corals or Arctic systems (see Figure 18-5). Evidence in both cases is *robust*. Outside of these systems, however, evidence is *limited* and highly localised. Recent detection and attribution literature has shed light on various components of the impact risk chain, but is otherwise limited in its extent for evaluating changes in impact risk for systems other than warm-water coral reefs and Arctic systems. Overall, observed impacts confirm reasons for concern about the risks of extreme weather events.

[INSERT FIGURE 18-5 HERE
Figure 18-5: Left: confidence in detection of observed changes in extreme weather hazards and attribution of a major role of changing greenhouse gas concentrations in the observed changes. Right: confidence in detection of observed changes in damages related to extreme weather and attribution of major role to observed changes in extreme weather.]

18.6.2.3. Distribution of Impacts

This RFC concerns the disparities of impacts between regions, countries, and populations. Evidence of differentiated climate change impacts have been projected for all IPCC regions since the days of the TAR. However, because of major geographical gaps in detection and attribution evidence the TAR did not report any observed regionally differentiated impacts, and nor did the AR4. The “before present” segments of the RFC box were therefore left uncolored in both the TAR and Smith *et al*. (2009). The survey of recent studies presented in 18.5 indicates that the gap is being reduced. While evidence for detected impacts is still more exhaustive from Europe and North America, considerable confidence in conclusions has been developed elsewhere since the AR4, particularly in Central and South America and Australasia. Tables 18-6 through 18-9 summarize what we have learned from the more recent evidence, as assessed in this chapter and other chapters throughout this report based on a consistent interpretation of the underlying criteria. Figure 18-6 portrays the assessment visually.

In terms of level of confidence, it is no longer the case that observed evidence to support the regional RFC is dominated by any particular region. The number of studies and coverage of systems may still be asymmetrically distributed, but rigorous analyses of observed climate change effects and attribution (to a lesser but not insignificant degree) have emerged from Central and South America, Australasia, Asia, Africa, and Small Islands. The synthesis of assessments for natural systems in the middle-to-high range for detection and the middle-to-high range for detection and attribution spans all major regions. The number of systems covered is only an indicative metric of coverage, because many options exist for aggregation and disaggregation of evidence. Thus detection and attribution analyses currently do not provide evidence of differing severity of impacts between continents. There exists, however, a particular emphasis on evidence concerning the Arctic where systems exhibit a high sensitivity to

climate change. Given the strong levels of confidence in changes across a broad range of Arctic systems, this emphasis indicates a stronger severity of impacts on the Arctic generally.

Coverage of human and managed systems is noticeably less extensive and more concentrated in the traditionally well-studied regions. Notwithstanding these differences, the qualitative conclusion that observed impacts have now been detected and attributed with *medium* to *high confidence* across the various IPCC-defined regions of the world is new and noteworthy. These higher confidence impacts generally concern the UNFCCC's metric that "food production is not threatened"; confidence in detection and attribution of observed impacts in other human systems generally remains much lower.

Throughout its assessments, the IPCC has repeatedly noted that there is significant disparity between the vulnerability of countries, regions, and social groups, due to differences in adaptive capacity. The AR4 cited examples that indicate how impacts of extreme events differ between social groups (Wilbanks *et al.*, 2007). The current coverage of detection and attribution studies is insufficient for broad evaluation of social disparities in impacts. Additional research effort is required to more fully address the nature of differences in impacts on various groups (18.7).

[INSERT FIGURE 18-6 HERE
Figure 18-6: Confidence in detection of observed changes in natural systems (panel a) and human and managed systems (panel b) across regions, and confidence in attribution of such trends to observed climate change. Based on assessments developed in Tables 18-6 through 18-9.]

18.6.2.4. Aggregate Impacts

The original intent of the Aggregate Impacts (or Aggregate Damages) RFC was to assess economic impacts, damages, and economic risk driven by climate change at a globally aggregated level. However, while some observed impacts are calibrated using a common monetary currency, others are now directly measured in a common calibrated metric or are otherwise qualitatively comparable across the globe and thus amenable to aggregation. In recognition of this, the scope of the RFC has been expanded over time (Smith *et al.*, 2009). Consequently, a variety of globally comparable impacts are considered here.

Table 18-2 lists various aggregate systems for which: the extent is global or near-global; there is a quantitatively or qualitatively calibrated measure for comparison across space and subsystems; the detection and attribution evidence has sufficient geographical distribution for a spatially representative sample. Confidence assessments for both detection and attribution span a wide range. Confidence is highest in cryospheric systems (glaciers and permafrost), with confidence in detection at least *medium* for various ecosystem measures but confidence in attribution lower (see Figure 18-7). Within human and managed systems, confidence in attribution to observed climate change is *low or very low* because of the dominating contribution of other drivers of change, including increased wealth, changes in exposure, new crop varietals, and new technologies. Overall, detection and attribution analysis reveals evidence for concern that risk of changes in aggregate measures has already changed, but also reveals *limited evidence* of a climate change influence on aggregate measures which do not concern the cryosphere.

Overall, the synthesis of aggregated impact measures confirms the concern for globally aggregated impacts of recent climate change being detected for a variety of systems and metrics.

[INSERT TABLE 18-12 HERE
Table 18-12: Confidence in detection of impacts on aggregate impact measures and confidence in attribution of at least a minor role of climate change in those observed changes.]

[INSERT FIGURE 18-7 HERE
Figure 18-7: Confidence in detection of changes in aggregate impact measures and attribution of at least a minor role of climate change in those trends]

18.6.2.5. Risks of Large-Scale Discontinuities

The RFC of "Risks of Large-Scale Discontinuities" "represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts" (Smith *et al.*, 2009). Such discontinuities are hence a source of future risk, as they refer to thresholds in the Earth system that, once passed, will alter the nature of the system itself. While several of the identified "tipping elements" form part of the physical climate-ocean-cryosphere system (and are discussed in WGI), there are also elements in the biosphere that exhibit non-linear behavior with potentially strong feedbacks on the Earth system (Lenton *et al.*, 2008; Leadley *et al.*, 2010).

For observed impacts, the concern translates into a question of the possible presence of "early warning signals" for discontinuities that may be derived from monitoring changes in some climate or natural systems (Collie *et al.*, 2004; deYoung *et al.*, 2008; Andersen *et al.*, 2009; Lenton, 2011). To this effect, conceptual, observational and modelling studies of climate-change-induced biome or large-scale ecological regime shifts have intensified over the last decade (deYoung *et al.*, 2008; Marengo *et al.*, 2011; e.g., Duarte *et al.*, 2012b; Mann *et al.*, 2012).

Evidence from detection and attribution analysis supports concerns that both the Arctic and the global warm-water coral reef system are experiencing irreversible regime shifts, attributable to recent climate change, while observations from the boreal and Amazon forest are less conclusive.

- For the Arctic region, new evidence indicates a biophysical regime shift is taking place, with social and economic consequences (Post *et al.*, 2009; CAFF, 2010; Callaghan *et al.*, 2010; AMAP, 2011; Duarte *et al.*, 2012b, see also 18.3.1, 24.4.2.2, 28.2). For the marine biota in the Arctic Ocean, the rapid reduction of summer ice cover is now severely affecting pelagic ecosystems as well as ice-dependent mammals such as seals and polar bears (Duarte *et al.*, 2012a). Thawing of Arctic permafrost and shrub encroachment on the tundra have both been detected with *high confidence* (18.3.2.4, 18.5.8, 24.4.2.2), driven by warming and an associated prolongation of the growing season. Wide-spread hydrological changes have been observed in the tundra region, as a result of increasing winter rains and the degradation of permafrost, leading to lake formation or disappearance within a few years' time (CAFF, 2010; Callaghan *et al.*, 2013) and cascading consequences for the tundra food webs (Post *et al.*, 2009; Callaghan *et al.*, 2013; Hansen *et al.*, 2013).
- Warm-water coral reefs have been lost at a large scale due to thermal stress and other impacts, as was noted by AR4 already. Increased mass bleaching and mortality of corals has been detected and attributed globally with *very high confidence* (see Box 18-3), with at least *high confidence* regionally in tropical Asia, Japan, the Australian Great Barrier Reef, the western Caribbean and coast of Central America, and the waters around other small tropical islands (6.3.2, 24.4.3.2, 27.3.3.1, 29.3.1.2). This irreversible loss of biodiversity has significant feedbacks within the marine biosphere, and cascading consequences for regional marine ecosystems as well as the human livelihoods which depend on them. The additional evidence for ongoing change and its attribution to warming gained since the AR4 strengthens the conclusion that coral reef loss constitutes a strong warning signal for the irreversible loss of an entire biome.
- Dieback and degradation in the Boreal forests and the Amazonian rainforest have been identified as potential tipping elements, due to their large extent and the possible feedbacks with the carbon cycle (Lenton *et al.*, 2008; Malhi *et al.*, 2009; Leadley *et al.*, 2010; Marengo *et al.*, 2011, see also 4.3.3.1, 4.3.3.4). For the boreal forest, increases in tree mortality are observed in many regions (4.3.3), including wide-spread dieback related to insect infestations in North America (26.4.1), but there is *low confidence* in detection of this as a global trend attributable to climate change. In the humid tropical forests of the Amazon basin, tree turnover (both mortality and growth) has increased during recent decades. A number of factors have likely played a role, including the direct effect of rising CO_2 on lianas, recovery from past disturbance, and changing climate. The reason for concern about the Amazon forest is the interaction between global climate change, regional climate change related to deforestation, and the high susceptibility of forests to fire, which together could lead to degradation of forests in large areas of the Amazon above deforestation itself (Malhi *et al.*, 2009). There are indications of droughts in the Amazon and evidence that dry years and deforestation increase the vulnerability of forests to fire, but there is only *very low confidence* in attribution of observed changes in tree turnover to climate change. In conclusion, there is currently

insufficient evidence from observed climate change impacts to support a climate-related warning sign of possible large-scale discontinuities in the boreal and Amazonian forest.

In the TAR, the risk of large-scale discontinuities was evaluated to be a concern only after a few degrees warming. At the time of the AR4, new understanding of physical climate processes led to a major revision of that assessment by Smith *et al*. (2009), bringing concerns forward that discontinuities could occur with much less warming. While the present analysis does not indicate the manifestation of a tipping point being reached, it does indicate significant early warning indicators for possible regime shifts in the Arctic region and for the world's warm-water coral ecosystems. Observations therefore confirm the reasons for concern about risks from large-scale singularities.

18.6.3. Conclusion

The body of scientific evidence on observed impacts of recent climate change, after rigorous assessment of scientific confidence in its attribution to recent trends, lends new qualitative support to four out of five reasons for concern established by earlier IPCC assessments. Specifically, concerns are confirmed for risks to unique and threatened systems, risks stemming from extreme weather events, globally aggregated impacts and – in terms of early warnings – risks of large-scale discontinuities. Only the spatial or social disparities covered under "distribution of impacts" are still insufficiently studied to permit a synthesis of available observations for the characterization of a global concern. While the Arctic stands out as a region with robust evidence of impacts across numerous systems, current detection and attribution literature does not address whether the severity of those impacts differs from other regions. Across RFCs, the critical evidence often comes from the same environmental systems, notably the Arctic region, warm-water coral reef systems and mountain glaciers, but there are also important observations from impacted hydrological systems and human systems including agriculture.

Detection and attribution studies evaluate the agreement between observations and process understanding, with the important requirement for direct observational evidence of the impacts. This sets a higher bar for establishing confidence in past changes than is generally used for assessing confidence in projected future changes, because observational evidence has important gaps, while the plausibility of future changes can be established on the basis of process knowledge only (WGI AR5 Chapter 10.2.5).

Despite this constraint, the evidence gathered since the AR4 on detection and attribution of observed impacts from climate change has reached a level at which it can inform evaluation of many of the aspects of present-day climate change risk as described by the RFCs. In particular, the geographic distribution of studies is reaching the point where assessment of the global nature of impacts is possible:

- There is now *robust evidence* of observed changes in natural systems in all of the regional groupings used in this report. There is at least *medium confidence* in attribution of observed changes in various components of the cryosphere to observed climate change for each of the inhabited continents. There is also at least *medium confidence* in attribution of observed changes in terrestrial ecosystems to observed climate change for six continents (exception being South America) and for some small islands, and for marine ecosystems surrounding six continents (exception being Africa) and for some small islands.
- There is *good evidence* of the detection of impacts in human systems on the inhabited continents. There is at least *medium confidence* in detection of impacts on food production in all the inhabited continents.
- While the current detection and attribution literature does not reveal observational evidence of geographical differences in the severity of climate change impacts between continents, it does indicate that the unique systems of the Arctic region and warm water coral reefs are undergoing rapid changes in response to observed warming in ways that are potentially irreversible.

18.7. Gaps, Research Needs, Emerging Issues

While the literature formalizing accepted approaches and methods for detection and attribution studies on human and natural systems is relatively recent, the underlying question is one with a long tradition: how to detect a relationship between cause (climate change) and effect (impacts)? The literature on climate change impacts has

largely focused on providing estimates of *future* impacts covering the globe and almost any possible affected human and natural system, *observed* impacts have received comparably little attention. In order to provide better guidance for the policy-relevant risk assessment of future impacts, the coverage of impacts that have already occurred needs to be strengthened

With the exception of the food system, detection and attribution studies are most scarce in human systems. While sensitivity to climate variability is clear for many important economic sectors and infrastructures, this is not mirrored in the literature available on observed impacts of climate change.

In part, this is due to the fact that human systems are extremely complex and evolving at a very rapid pace, with many other drivers and their interactions challenging assessments of the comparatively weak recent climate signals. Human systems are also capable of autonomous and planned adaptation, including adaptation to predicted climate change, complicating the diagnosis of impacts of observed climate change. The literature on observed climate adaptation response is sparse. More fundamentally, much of the research on the relation between past climate change and impacts in human systems has been of a nature that has not fit into the deterministic, quantitative detection and attribution framework adopted in earlier Assessment Reports (Stone *et al.*, 2013). Fully including human systems into a complete understanding of observed impacts should be a priority for assessing future vulnerability to climate change.

The current detection and attribution literature does not provide a sufficiently comprehensive sampling of the distribution of impacts around the world, for instance between poor and wealthy populations. This dearth of studies reflects inadequate or a lack of long term monitoring or observational systems, an insufficient network density of meteorological observations, and/or lack of research funding, together leading to limited research capability. One other important reason is that in some sub-regions, particularly in the tropics, temperature sensitivities are poorly understood because rainfall is the primary climate driver, and precipitation trends under anthropogenic climate change are not as clearly understood as temperature trends.

Another challenge lies in addressing changes in impacts of extreme weather events and their relation to climate change, as well as determining the role of climate change in special events in impact systems. In some cases difficulty arises from dominating influences of non-climate factors on the extent of actual impacts of extreme weather events and the often highly nonlinear interactions of those factors, but a general characteristic lies in the difficulty of characterizing changes in the frequency or intensity of events that occur only very rarely.

Frequently Asked Questions

FAQ 18.1: What are the main challenges in detecting climate change impacts?

Detection addresses the question of whether a system has changed beyond its expected behavior in the absence of climate change. One challenge in detection is distinguishing between a change in a system and natural variability in the system. Most natural and human systems will exhibit variability over time even in the absence of a change in external factors. Particularly over short periods of time, this kind of natural variability can give the appearance of a systematic change. For example, even in the absence of changes in external factors, some wild populations can undergo prolonged periods of boom or bust. Distinguishing natural variability from systematic change usually requires an understanding of the charateristics of the former. This can be based on an analysis of historical data or an understanding of the dynamics of the system. A second challenge to detection is distinguishing between between a change in the system that is potentially attributable to climate change and one that is due to a change in non-climatic factors. For example, wild populations may change as a result of harvesting or habitat loss unconnected to climate change. Distinguishing such changes from those potentially attributable to climate change requires an understanding of the non-climatic factors that can affect the system and how these factors have changed.

FAQ 18.2: What is the main challenge in attributing changes in a system to climate change?

Attribution addresses the question of whether changes detected in a system can be attributed to climate change. Once a climate-related effect on a system has been detected, the main challenge in attribution is determining whether this effect is due to climate change rather than natural climate variability. For example, widespread flooding

in Australia and other parts of the western Pacific during 2010 and 2011 was caused by unusually heavy rainfall. However, this heavy rainfall was found to be related to the occurrence of La Niña, part of the naturally occurring ENSO variation, and therefore the flooding is not attributable to climate change.

FAQ 18.3: Why are detection and attribution of climate impacts important?

In deciding how to respond to climate change, policy-makers and others need to understand what the future impacts of climate change will be. One way to gain understanding about the future impacts of climate is to identify impacts of climate change that has already occurred. For example, it has been predicted that climate change will cause a poleward shift in the geographical ranges of species. Detecting such a shift in response to climate change that has already occurred would tend to validate this prediction.

FAQ 18.4: Is it possible to attribute a single event, like a disease outbreak or the extinction of a species, to climate change?

Scientists are usually reluctant to attribute a single event to climate change and instead tend to focus on the frequency or severity of classes of events. One reason for this is that the scientific knowledge needed to attribute a single event to climate change is much greater than that needed to attribute a change in the frequency or severity of classes of events. For example, there is good evidence that there has been an increase in the frequency of heat waves in many parts of the world and that this increase can be attributed to climate change. However, claiming that, in the absence of climate change, a particular heat wave would not have occurred is largely beyond present scientific capabilities.

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Table 18-1: Observed changes in ocean system properties and their effects, with confidence levels for detection and attribution to climate change, based on assessment in Chapter 6.2, 6.3, and summarized in 6.6.1 and Figure 6-16. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.

Process	**confidence in**		**Context**	**Ref**
	detection	**attribution**		
Impacts of ocean acidification on pelagic marine biota	*low*	*low*	e.g., reduction in foraminiferan, coccolithophores and pteropod shell weight. Attribution supported by experimental evidence and physiological knowledge	[1]
Expansion of midwater hypoxic zones	*high*	*med*	oxygen minimum zones (OMZs) caused by enhanced stratification and bacterial respiration due to effects of warming	[2]
Regional and local impacts of expanding OMZs	*medium*	*low - medium*	reduction of biodiversity, compression of oxygenated habitat for intolerant species, range expansion for tolerant taxa	[3]
Direct temperature effects on marine biota related to limited physiological tolerance ranges	*very high*	*high*	e.g., large scale latitudinal shifts of species distribution, changes in community composition; attribution supported by experimental and statistical evidence as well as physiological knowledge	[4]
Increase in global net primary production	*medium*	*low*	discrepancy between satellite observations and open ocean time-series sites; in higher latitudes, NPP is increasing due to sea ice decline and warming	[5]
Changes in microbial processes	*low*	*low*	*low confidence* and limited understanding of microbial processes, drivers and interactions	[6]
Large scale shifts in biogeochemical pathways	*low*	*low*	*low confidence* for large scale shifts in biogeochemical pathways such as oxygen production, carbon sequestration and export production, nitrogen fixation, climate-feedback by DMS production, nutrient recycling	[7]

Key references and traceable account for the statements above:[1] (Wootton *et al*., 2008; De Moel *et al*., 2009; Moy *et al*., 2009; Bednaršek *et al*., 2012); 6.2.2, 6.3.4; [2] (Stramma *et al*., 2008; Stolper *et al*., 2010); 6.2.2; [3] (Levin *et al*., 2009; Ekau *et al*., 2010; Stramma *et al*., 2010; Stramma *et al*., 2012), 6.3.3; [4] (Merico *et al*., 2004; Perry *et al*., 2005; Pörtner and Farrell, 2008; Beaugrand *et al*., 2010; Alheit *et al*., 2012); 6.2.2, 6.3.2; [5] (Behrenfeld *et al*., 2006; Saba *et al*., 2010; Arrigo and Van Dijken, 2011); 6.3.1; [6] 6.2.2.4; [7] 6.3.3;6.3.4;6.3.5

Table 18-2: Observed changes on marine species and ecosystems, with confidence levels for assessment of detection of changes and their attribution to climate change, based on assessment in Chapter 6.2, 6.3, summarized in 6.6.1 and Figure 6-16, and 30.4. Observed impacts related to temperature effects have been attributed to warming, although the relative contributions of regional climate variation and long-term global trends have not been quantified.

Process	**confidence in**		**Context**	**Ref**
	detection	**attribution**		
Range shifts of fish and macroalgae	*high*	*high*	changes in species biogeographical ranges to higher latitudes or greater depths	[1a]
Changes in community composition	*high*	*high*	due to effects of warming, hypoxia, and sea ice retreat	[1b]
Changes in abundance	*high*	*high*	observed in fish, corals and intertidal species	[1c]
Impacts on marine air breathers, e.g. walruses, penguins, and other sea-birds	*high*	*high*	observed effects include changing abundance, phenology, species distribution and turtle sex ratios, and are mostly mediated through changes in resource availability including prey	[2]
Impacts on warm-water reef-building corals	*very high*	*very high*	effects mostly attributed to warming and rising extreme temperatures, though ocean acidification may contribute	[3]
Increments in fish species richness in temperate and high latitude zones	*high*	*medium*	effect associated with loss of sea ice and latitudinal species shifts due to warming trends	[4]
Change in regional fishery catch potential due to species shifts	*high*	*high*	partly attributable to climate change, and to fishing pressure	[5]
Change in fishery catch potential following changes in net primary production	*low*	*low*	effect associated with warming	[6]

Key references and traceable account for the statements above: [1a,b,c] (Müller *et al*., 2009; Stige *et al*., 2010); 6.3.2, 30.4; [2] (Grémillet and Boulinier, 2009; McIntyre *et al*., 2011); [3] (Hoegh-Guldberg, 1999; Hoegh-Guldberg *et al*., 2007; Baker *et al*., 2008; Veron *et al*., 2009); [4] (Hiddink and ter Hofstede, 2008; Beaugrand *et al*., 2010); 6.3.7, 6.5.2; [5] Figure 6-16.5a; [6] Figure 6-16 5b

Table 18-3: Confidence in detection and attribution of observed climate change effects across ocean regions, based on expert assessment in Chapter 30.5 (respective subsections are given below). Confidence levels assigned are for detection / attribution, respectively.

	high latitude spring bloom systems	**equatorial upwelling**	**semi-enclosed seas**	**coastal boundary systems**	**Eastern boundary upwelling ecosystems**	**Subtropical gyres**
	30.5.1	30.5.4	30.5.6	30.5.3	30.5.2	30.5.5
Regional warming	*very high-high / high*	*very high-high / very high-high*	*very high-high / high*	*very high / high*	*medium/medium-low**	*very high-high / very high-high*
Declining oxygen	*medium / medium-low*	*medium / medium-low*	*medium / medium-low*	*high / medium*	*medium / medium*	*medium / low-medium*
Declining primary productivity	n/s	n/s	n/s	*medium / medium-low*	*medium-low / medium-low*	*medium / medium*
Shifts in phenology	*high / high-medium*	n/s	*medium / medium-low*	*medium / medium-low*	*medium / medium-low*	n/s
Changes in abundance and species distribution	*high / high*	n/s	*high / high*	*medium / medium-low*	*medium / medium-low*	n/s

* California and Canary systems only

Table 18-4: Illustrative selection of some recent extreme impact events for which the role of climate has been assessed in the literature. The table shows confidence assessments as to whether the associated meteorological events made a substantial contribution to the impact event, as well as confidence assessments of a contribution of anthropogenic emissions to the meteorological event. The assessment of confidence in the findings is not necessarily a conclusion of the listed literature but rather results from assessment of the literature. Assessment of the role of anthropogenic emissions in the impact event requires a multi-step evaluation. Partly based on Coumou and Rahmstorf (2012).

Year	**Region**	**Extreme impact event**		**Meteorological Event**	
		Impact / damage	**Confidence in contribution of extreme weather event to observed damage**	**Meteorological event**	**Confidence in contribution of anthropogenic emissions to extreme weather event**
2003	Europe	excess death toll exceeding 70,000 *(Robine et al., 2008)*	*very high*	hottest summer in at least 500 years (Luterbacher *et al.*, 2004; Schär and Jendritzky, 2004; Stott *et al.*, 2004; Christidis *et al.*, 2010)	*high*
2005	North Atlantic / USA	1,700 deaths and over US$100 Bn in damage (Beven *et al.*, 2008)	*very high*	record number of tropical storms, hurricanes and category 5 hurricanes since 1970 (Emanuel, 2005; Webster *et al.*, 2005; Trenberth and Shea., 2006; Pielke Jr *et al.*, 2008; Vecchi *et al.*, 2008; Landsea *et al.*, 2009; Knutson *et al.*, 2010)	*very low*
2006-2007	Europe	partial second flowering or extended flowering in 2006, early flowering in 2007 (Luterbacher *et al.*, 2007)	*high*	hottest record fall and winter in at least 500 years (Luterbacher *et al.*, 2007; Van Oldenborgh, 2007; Yiou *et al.*, 2007; Cattiaux *et al.*, 2009)	*medium*
2010	Western Russia	burned area > 12,500km (Müller, 2011)	*low*	hottest summer since 1500 (Barriopedro *et al.*, 2011; Dole *et al.*, 2011; Rahmstorf and Coumou, 2011; Otto *et al.*, 2012)	*medium*
2011	Thailand	prolonged (up to 2 month) inundation of urban and industrialized areas, insured loss US$ 8-11 B, total loss ca. US$45 (SwissRe, 2011; WorldBank, 2011)	*very high*	wettest monsoon on record in middle and upper Chao Phraya Basin (Van Oldenborgh *et al.*, 2012)	*very low*
2010	Colombia	exceptionally heavy rainfall and floods, 4 M people affected, US$ 7.8 Bn total damage (Hoyos et al., 2013)	*very high*	ENSO-related second and third highest SST in Caribean on record in late 2010; second most active storm and hurricane season (Trenberth and Fasullo, 2012)	*low*
2010	Pakistan	worst ever known floods in the region, 2000 people killed, 20 M affected, total loss US$ 40Bn (Hong *et al.*, 2011)	*very high*	Exceptionally high rainfall amounts over northern Pakistan with unusual atmospheric circulation patterns (Houze Jr *et al.*, 2011; Webster *et al.*, 2011; Galarneau *et al.*, 2012)	*very low*
2011	Queensland, Australia	>200,000 people affected, >30,000 homes flooded, damages and cost to economy US$ 2.5 – 10 B (Van den Honert and McAneney, 2011; Hayes and Goonetilleke, 2012)	*very high*	2010 wettest year on record for Queensland, with extreme precipitation in January 2011 on saturated ground; record high Southern Oscillation Index in 2010 (Van den Honert and McAneney, 2011; Cai and Van Rensch, 2012; Hayes and Goonetilleke, 2012)	*low*

Table 18-5: Cases of regional livelihood impacts attributable with varying degree to weather- and climate related events, climate change or climate variability.

Impacted Population	Climate-related driver	Impact on livelihood	Reference
Small-scale farmers, Ghana	Drought	Landscape transformation, poverty	(Tschakert *et al*., 2011)
Middle-class farmers, Australia	Drought	Landscape transformation, income loss from agriculture, social conflict, poverty	(Alston, 2011)
High Arctic native people	Warming	Changing ice and snow conditions, dwindling access to hunting grounds	(Ford, 2009a; Ford, 2009b, see also Box 18-5)
Urban populations in Maputo, Accra, Nairobi, Lagos, Kampala	Flood frequency and severity increase	Direct impacts on people and loss of physical assets (e.g. housing)	(Douglas *et al*., 2008)
Industry workers in India	Temperature variability and heat waves	Limited ability to carry out physical work, health impacts	(Ayyappan *et al*., 2009; Balakrishnan *et al*., 2010; Dash and Kjellstrom, 2011)
Farmers in Subarnabad, Bangladesh	Sea-level rise	Salt water intrusion, shift from agriculture to shrimp farming, loss of agricultural livelihoods	(Pouliotte *et al*., 2009)
Women farmers, Ghana	Rainfall-related climate variability	Pressure from husbands limiting involvement in agriculture, poverty	(Carr, 2008)
Cambodian rice farmers	Warming, rainfall-related climate variability	Shift in income generation patterns between men and women	(Resurreccion, 2011)
Poor children in Africa and Latin America	Weather and climate-related events	Food price shocks, reduced caloric intake, physical stunting, long-term effects such as reduced lifetime earnings	(Alderman, 2010)
Smallholder farmers in highlands of Bolivia	Rising temperatures and higher variability in weather and climate-related extremes	Stress on household resources due to need to respond to increasing plant pests, switching to other crop types or livestock	(McDowell and Hess, 2012)

Table 18-6: Observed impacts of climate change on snow, ice and mountains, and rivers and lakes, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Snow, Ice and Mountains	Rivers and Lakes
Africa	**Retreat of tropical highland glaciers in East Africa** *very high* / *medium confidence* [22.5.1, (Mölg *et al*., 2008; Taylor *et al*., 2009; Mölg *et al*., 2012)]	**Reduced discharge in West African rivers** *medium* / *low confidence* (d'Orgeval and Polcher, 2008; Dai *et al*., 2009; Di Baldassarre *et al*., 2010) **Decreased flood frequency in Okavango delta** *low* / *low confidence* (Wolski *et al*., 2013) **Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba** *high* / *high confidence* [22.3.2.2, (Tierney *et al*., 2010; Ndebele-Murisa *et al*., 2011; Powers *et al*., 2011)]
Europe	**Retreating glaciers in the Alps** *very high* / *high confidence*, (Bauder *et al*., 2007; Paul and Haeberli, 2008; Zemp *et al*., 2008; Zemp *et al*., 2009) **Increase in rock slope failures in Western Alps** *high* / *medium confidence* [18.3.1.4; (Fischer *et al*., 2012; Huggel *et al*., 2012a)]	**Changes in the occurrence of extreme river discharges and floods** *low* / *very low confidence* (Schmocker-Fackel and Naef, 2010; Beniston *et al*., 2011; Cutter *et al*., 2012; Vorogushyn and Merz, 2012; Kundzewicz *et al*., 2013)
Asia	**Permafrost degradation in Siberia, Central Asia, and the Tibetan Plateau** *high* / *high confidence* [Box 3-2, WGI AR5 Chapter 10.5.3, (Romanovsky *et al*., 2010; Yang *et al*., 2012)] **Mountain glaciers across Asia are shrinking** *high* / *medium confidence* [WGI AR5 Chapter 4.3.2-4.3.3; Box 3-1; (Bolch *et al*., 2012; Cogley, 2012; Kääb *et al*., 2012; Yao *et al*., 2012; Gardner *et al*., 2013; Stokes *et al*., 2013)]	**Changes in water availability in many Chinese rivers** *high* / *low confidence* [24.4.1.2; (Casassa *et al*., 2009; Zongxing *et al*., 2010)] **Increased runoff in many rivers due to shrinking glaciers in the Himalayas and Central Asia** *high* / *high confidence* [24.4.1.2; Box 3-1; (Casassa *et al*., 2009; Zongxing *et al*., 2010; Shrestha and Aryal, 2011; Zhang *et al*., 2011)] **Surface water degradation in various parts of Asia partially related to climate change** *medium* / *medium confidence* [24.4.1.2; (Prathumratana *et al*., 2008; Delpla *et al*., 2009; Huang *et al*., 2009)] **Earlier timing of maximum spring flood in Russian rivers** *high* / *high confidence* [28.2.1.1; (Shiklomanov *et al*., 2007; Tan *et al*., 2011)]
Australasia	**Reduction in glacier ice volume in New Zealand** *high* / *low confidence* [WGI AR5 Chapter 4.3.3; Table 25-1; (Nicholls, 2006; Chinn *et al*., 2012)] **Significant decline in late-season snow depth at four alpine sites in Australia (1957-2002)** *high* / *medium confidence* (Hennessy *et al*., 2008)	n/s

North America	**Observed snowpack show primarily decreasing trends** in the amount of water stored in spring snowpack from 1960-2002 *high / high confidence* (Stewart *et al*., 2005; Mote, 2006)	**Observed shift to earlier peak flow in snow dominated rivers in Western North America** *high / high confidence* [WGI AR5 Chapter 2.6.2; (Barnett *et al*., 2008)] **Runoff increases in the Midwestern and Northwestern US, decreases in Southern states** *high / medium confidence* (Georgakakos *et al*., 2013)
South and Central America	**Retreat of tropical Andean glaciers** in Venezuela, Colombia, Ecuador, Peru and Bolivia (second half of the 20th century) and glaciers and ice-fields in the extra tropical Andes (Central-South Chile and Argentina) *high / high confidence* [27.3.1.1; (Vuille *et al*., 2008; Bradley *et al*., 2009; Jomelli *et al*., 2009; Poveda and Pineda, 2009; Rabatel *et al*., 2013)] **Increased landslide frequency due to heavy precipitation in SE South America** *medium / low confidence* [27.2.1.1; (Donat *et al*., 2013; Marengo *et al*., 2013; Silva Dias *et al*., 2013)]	**Changes in extreme flows in Amazon River** *high / medium confidence* [27.2.1.1; (Rodríguez-Morales *et al*., 2010; Butt *et al*., 2011; Wang *et al*., 2011; Espinoza *et al*., 2013)] **Changes in discharge patterns in rivers in the Western Andes** due to retreating glaciers and reduced snowpack; for major river basins in Colombia discharge has decreased during the last 30-40 years *high / high confidence* [27.3.1.1; (Vuille *et al*., 2008; Bradley *et al*., 2009; Jomelli *et al*., 2009; Poveda and Pineda, 2009; Rabatel *et al*., 2013)] **Increased stream flow in Sub-basins of the La Plata River**, attributed to increasing precipitation, but also to trends in land use changes that have reduced evapotranspiration *very high / high confidence* [27.3.1.1; (Pasquini and Depetris, 2007; Krepper *et al*., 2008; Conway and Mahé, 2009; Krepper and Zucarelli, 2010; Doyle and Barros, 2011)]
Polar Regions	**Decreasing Arctic sea ice cover in summer, reduction in glacier ice volume**, due to warming *high / high confidence* [WGI AR5 Chapter 10.5.1.1; (ACIA, 2005; AMAP, 2011)] **Decreasing snow cover duration across the entire Arctic** *high / medium confidence* [28.2.3.4, 5; (AMAP, 2011; Callaghan *et al*., 2011)] **Widespread permafrost degradation**, especially in the southern Arctic *high / high confidence* (AMAP, 2011; Olsen *et al*., 2011) **Increased ice mass loss along coastal Antarctica** *medium / very low* [WGI AR5 Chapter 4.2.3, 4.4, 4.6, 10.5.2.1]	**Increased river discharge for large circumpolar rivers** (1997–2007) *high / low confidence* [28.2.1.1; (Overeem and Syvitsky, 2010)] **Winter minimum flows have risen in most sectors of the Arctic** due to enhanced groundwater input due to permafrost thawing *high / medium* [28.2.1.1; (Tan *et al*., 2011)] **Increasing surface lake water temperatures 1985–2009 and prolonged ice-free seasons**, due to warming *medium / medium confidence* [28.2.1.1; (Callaghan *et al*., 2010; Schneider and Hook, 2010)] **Thermokarst lakes disappear due to permafrost degradation in the low Arctic, while new ones are being created in areas of formerly frozen peat** *high / high confidence* (Riordan *et al*., 2006; Marsh *et al*., 2008; Prowse and Brown, 2010)

Table 18-7: Observed impacts of climate change on terrestrial ecosystems, and occurrence of drought and wildfires, across eight major world regions, with confidence in detection/confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Terrestrial Ecosystems	**Drought and Wildfire**
Africa	**Tree density decreases in Sahel and semi-arid Morocco** *high / medium confidence* [22.3.2.1.2; (Gonzalez *et al*., 2012; Le Polain de Waroux and Lambin, 2012)] **Climate-driven range shifts of several southern plants and animals**: South African bird species polewards; Madagascan reptiles and amphibians upwards; Namib aloe contracting ranges. *high / medium confidence* [22.3.2.1; (Foden *et al*., 2007; Raxworthy *et al*., 2008; Hockey and Midgley, 2009; Hockey *et al*., 2011)]	**Increased drought in the Sahel since 1970, partially wetter conditions since 1990** *medium / medium confidence* [22.2.2.1; (Hoerling *et al*., 2006; Giannini *et al*., 2008; Greene *et al*., 2009; Seneviratne *et al*., 2012)] **Wildfires increase on Mt. Kilimanjaro** due to warming and drying trends *medium / low confidence* [22.5.1; (Hemp, 2005)]
Europe	**Earlier greening, earlier leaf emergence and fruiting in temperate and boreal trees** *high / high confidence* [4.4.1.1; (Menzel *et al*., 2006)] **Increased colonization of alien plant species in Europe** *medium / medium confidence* [4.2.4.7; (Walther *et al*., 2009)] **Earlier arrival of migratory birds in Europe since 1970** *medium / medium confidence* [4.4.1.1; (Møller *et al*., 2008)] **Upward shift in tree-line in Europe** *medium / low confidence* [18.3.2.1; (Gehrig-Fasel *et al*., 2007; Lenoir *et al*., 2008)]	**Increasing burnt forest areas during recent decades** *high / high confidence* (Hoinka *et al*., 2009; Koutsias *et al*., 2012)
Asia	**Changes in plant phenology and growth occur in many parts of Asia**, observed from ground observations as well as from satellites (earlier greening), particularly in the North and the East *high / medium confidence* [24.4.2.2; 4.2.1, Box 4-1; (Ma and Zhou, 2012; Panday and Ghimire, 2012; Shrestha *et al*., 2012; Ogawa-Onishi and Berry, 2013)] **Many plant and animal species have shifted their distribution**, particularly in the North of Asia, generally upwards in elevation or polewards *high / medium confidence* [24.4.2.2; (Moiseev *et al*., 2010; Chen *et al*., 2011; Jump *et al*., 2012; Ogawa-Onishi and Berry, 2013)] **Siberian larch forests are being invaded by pine and spruce during recent decades, Mongolian larches show decreasing growth** *medium / low confidence* (Kharuk *et al*., 2010; Dulamsuren *et al*., 2011; Lloyd *et al*., 2011) **Advance of shrubs into the Siberian tundra** *high / medium* confidence [28.2.3.1; (Blok *et al*., 2011)]	

Australasia	**Climate-related changes in genetics, growth distribution and phenology of many species** (earlier emergence of butterflies, change in plant flowering dates, breeding times of bird, decline in body size of passerine birds etc.) *medium / medium confidence* [table 25-3; (Green, 2010; Kearney *et al.*, 2010; Keatley and Hudson, 2012)] **Change in timing of migration of water and land birds in Australia** possibly due to changes in precipitation rather than changes in temperature *low / low confidence* [25.6.1, Table 25-3; (Chambers, 2008)] **Expansion of some wetlands and corresponding contraction of adjacent woodlands in SE Australia** *medium / low confidence* [table 25-3; (Banfai and Bowman, 2007; Bowman *et al.*, 2010; Keith *et al.*, 2010)]	**No significant change in drought occurrence in Australia** (over 20th century, using rainfall only) **or New Zealand** (since 1972, using a soil water balance model) *medium-low / n.a.* [table 25-1. 3.5.1; (Cai *et al.*, 2009; Potter *et al.*, 2010; Kingsford and Watson, 2011; IPCC, 2012)]
North America	**Species distribution shifts upward in elevation and northward in latitude across multiple taxa** *high / medium confidence* [26.4.1, 2; (Kelly and Goulden, 2008)] **Phenology changes** *high / medium confidence* [26.4.2; (Parmesan, 2006)] **Increases in tree mortality at regional scales and insect infestations in forests** *medium / low confidence* [26.4.1; (Peng *et al.*, 2011)]	**Increases in wildfire activity, including fire frequency and duration, length of fire season, and area burned** *high / medium confidence* [Box 26.2; (Westerling *et al.*, 2006)]
South and Central America	**Degrading and receding rainforest in the Amazon** *high / very low confidence* [27.2.2.1; (Etter *et al.*, 2006; Nepstad *et al.*, 2006; Oliveira *et al.*, 2007; Wassenaar *et al.*, 2007; Killeen *et al.*, 2008; Nepstad and Stickler, 2008)]	**Increase dryness for most of the west coast of South America and in the Andes between 35.6°S and 39.9°S since 1950** *medium / low confidence* [table 27-1; (Christie *et al.*, 2011; Dai, 2011)]
Polar Regions	**Increase in shrub cover in tundra in North America and Eurasia** *high / high confidence* [28.2.3.2; (Tape *et al.*, 2006; Walker *et al.*, 2006; Henry and Elmendorf, 2010; Blok *et al.*, 2011; Elmendorf *et al.*, 2012; Tape *et al.*, 2012)] **Significant advance of Arctic tree-line in latitude and altitude, due to warming**, although the pace is lower than expected due insect outbreaks, land use history *high / medium confidence* [28.2.3.3; (AMAP, 2011; Hedenås *et al.*, 2011; Van Bogaert *et al.*, 2011)] **Snow-bed ecosystems and tussock tundra are retreating, due to prolonged thawing season and less precipitation in the form of snow** *high / high confidence* [28.2.3.2; (Björk and Molau, 2007; Molau, 2010a; Hedenås *et al.*, 2011; Callaghan *et al.*, 2013)] **Animal populations in the tundra being affected by increasing occurrence of ice layers in the annual snow pack due to rain-on-snow events** *medium / medium confidence* (Callaghan *et al.*, 2013; Hansen *et al.*, 2013) **Breeding area and population size of subarctic birds has changed**, due to warming and shrub encroachment in the tundra *high / medium confidence* (Molau, 2010b; Callaghan *et al.*, 2013)	**Increasing drought in high Arctic polar deserts** *high / high confidence* [28.2.1.1; (Smol and Douglas, 2007)] **Increased frequency of wildfires in the conifer forest at the southern fringe of the Arctic**, due to increasing summer temperature *high / medium confidence* (Mann *et al.*, 2012) **Tundra wildfires are increasing in frequency in the Low Arctic,** due to increasing summer air temperature and subsequent surface drought *high / medium confidence* [28.2.3.6; (Mack *et al.*, 2011)]

	Plant species in the West Antarctic Peninsula and nearby islands have increased over the past 50 years *high / high confidence* [28.2.3.2; (Fowbert and Smith, 1994; Parnikoza *et al.*, 2009)] **Increasing phytoplankton productivity in Signy Island lake waters** *high / high confidence* [28.2.1.2; (Quayle *et al.*, 2002; Laybourn-Parry, 2003)]	
Small Islands	**Upward trend in tree-lines and associated fauna on high elevation islands** *low / low confidence* [29.3.2.1; (Benning *et al.*, 2002; Jump *et al.*, 2006)] **Changes in tropical bird populations in Mauritius, due to changes in rainfall** *medium / medium confidence* [29.3.2.1; (Senapathi *et al.*, 2011)]	**Increased drought frequency in Seychelles and Southern Jamaica** over past 30 years, decrease in rainfall over past 100 years in the Caribbean islands may have contributed to multiple water stress *low / very low confidence* [29.3.3.2; (Payet and Agricole, 2006; Cashman *et al.*, 2010; Gamble *et al.*, 2010)]

Table 18-8: Observed impacts of climate change on marine ecosystems, and coastal processes, across eight major world regions, with confidence in detection / confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Marine Ecosystems	**Coastal Processes**
Europe	**Poleward shifts in the distributions** of zooplankton, fish, seabirds and benthic invertebrate, and conversion of polar into more temperate and temperate into more subtropical system Characteristics in NE Atlantic *high / high confidence* [Table 6-8, 6.3.2, 30.5.1, 18.3.3.1, (Beaugrand *et al.*, 2009; Philippart *et al.*, 2011)] **Phenology changes and retreat of colder water plankton** to the north in the Northeast Atlantic, with mean poleward movement of plankton reaching up to 200–250 km per decade between 1958–2005 *medium / medium confidence* **[**6.3.2, Table 6-8, Fig 6-16; (Beaugrand *et al.*, 2002; Edwards and Richardson, 2004; Beaugrand *et al.*, 2009; Philippart *et al.*, 2011)] **Shift in distribution of Atlantic cod** due to warming, interacting with regime shift and regional changes in Plankton Phenology in North Sea *high / medium confidence* [6.3.2, Fig 6-16; (Perry *et al.*, 2005; Pörtner *et al.*, 2008; Beaugrand *et al.*, 2009; Beaugrand *et al.*, 2010)] **Decreasing abundance of eelpout** (Helcom indicator species) in Wadden Sea *medium / high confidence* [6.3.2, Fig 6-16; (Pörtner and Knust, 2007)]	

Asia	**Coral reefs and large seaweeds decline in tropical Asian and Japanese waters** *high / high confidence* [24.4.3.2; (Krishnan *et al.*, 2011; Nagai *et al.*, 2011; Coles and Riegl, 2012)] **Shift from sardines to anchovies in Japanese Sea** *medium / medium confidence* [6.3.22, Fig 16-6; (Takasuka *et al.*, 2007; Takasuka *et al.*, 2008)]	**Coastal erosion is accelerating in Arctic Asia**, due to changes in permafrost, storm wave energy and sea-ice retreat *medium / low confidence* (Razumov, 2010; Lantuit *et al.*, 2011; Handmer *et al.*, 2012)
Australasia	**Mass bleaching of corals in the Great Barrier Reef**, changes in coral calcification rates and changes in coral disease dynamics (e.g., black band disease, white syndrome) *high / high confidence* [6.3.2, 25.6.2, Box 18-3; (Cooper *et al.*, 2008; De'ath *et al.*, 2012)] **Multiple impacts of climate change on marine ecosystems from warming oceans**, although other environmental changes may play a role. Examples are increase of growth rates in fish, range shifts of intertidal invertebrates, retreat of seaweeds, range shift in near-shore fish related to kelp decline, increasing abundance of northern marine species in Tasmania, declines in recruitment of rock lobster and of abalone, decline in growth rate and biomass of phytoplankton, retreat of macroalgae, southward expansion of some tropical seabirds in Australia *high / high confidence* (Thresher *et al.*, 2007; Figueira *et al.*, 2009; Ling *et al.*, 2009; Pitt *et al.*, 2010; Chambers *et al.*, 2011; Neuheimer *et al.*, 2011; Wernberg *et al.*, 2011; Wernberg *et al.*, 2011, see also Table 25-3)	
North America	**Northwest Atlantic fish show northward range shift** in response to warming since the 1960s, with some of the shifts being correlated with the Atlantic multidecadal Oscillation *high / medium confidence* [Table 6-8, Fig 6-16 (Nye *et al.*, 2009; Lucey and Nye, 2010; Nye *et al.*, 2011)] **Earlier onset of migration of Pink Salmon in Alaska, collapse of spawning migration of Sockeye Salmon in Fraser River, BC**, due to warming *high / high confidence* [(Eliason *et al.*, 2011; Kovach *et al.*, 2012)] **Loss of biomass of midwater fish off California Coast** *high / high confidence* [6.3.3, 6.6.3]	**Coastal roads affected by flooding** during high tides in the US, though contribution of climate change to relative sea-level rise uncertain *low / very low confidence* (Moser and Davidson, 2013)
South and Central America	**Bleaching of coral reefs in the western Caribbean near the coast of Central America** *very high / high confidence* [27.3.3.1, (Guzman *et al.*, 2008; Manzello *et al.*, 2008; Carilli *et al.*, 2009; Eakin *et al.*, 2010)]	**Mangrove degradation on Northern South American coast** *high / low confidence* (Alongi, 2008; Lampis, 2010; Polidoro *et al.*, 2010; Giri *et al.*, 2011)
Polar Regions	**Many arctic and subarctic marine non-migratory mammals (walrus, seals, whales) are negatively affected by sea ice loss** *high / high confidence* [28.2.2.1.3, (Laidre *et al.*, 2008; McIntyre *et al.*, 2011)] **Reduced growth rate and body mass, lower survival and reproductive capacity of polar bears, linked to reduced off-shore range and sea-ice loss due to warming** *high / high confidence* [28.2.2.1.2; (Amstrup *et al.*, 2010)] **Arctic seabirds experience reduced reproductive success, due to earlier sea-ice break-up** *medium / medium confidence* [28.2.2.1.1; (Gaston *et al.*, 2009; Grémillet and Boulinier, 2009)]	**Increased coastal erosion in Arctic**, due to prolonged ice-free season at shore, increased exposure to wave activity, and degrading permafrost *high / high confidence* [28.2.4, 5; 28.3.4, (Forbes, 2011)]

	Acidification of Southern Ocean waters has resulted in reduced thickness of foraminifera shells *medium / medium confidence* [6.3.4, 28.2.2.2, (Moy *et al*., 2009)] **Antarctic krill density in the Scotia Sea has declined** by ca. 30 % since the 1980s, due to reduced winter sea ice extent and duration *medium / medium confidence* (Atkinson *et al*., 2004; Trivelpiece *et al*., 2011) **Many Southern Ocean species of seals and seabirds, e.g. penguins and Albatross, show negative responses to warmer conditions** *high / medium confidence* [28.2.2.2; (Croxall *et al*., 2002; Patterson *et al*., 2003; Jenouvrier *et al*., 2005; Véran *et al*., 2007; Forcada *et al*., 2008; Trathan *et al*., 2011)]	
Small Islands	**Coral bleaching near many tropical small islands** *high / high confidence* [29.3.1.2,3; (Alling *et al*., 2007; Bruno and Selig, 2007; Oxenford *et al*., 2008)] **Degradation of mangroves, wetlands and seagrass** in small islands, mostly due to disturbances and only a lesser extent possibly due to sea-level rise *high / low confidence* [29.3.1.4; (McKee *et al*., 2007; Gilman *et al*., 2008; Schleupner, 2008; Krauss *et al*., 2010; Marbà and Duarte, 2010; Rankey, 2011)] **Degradation of freshwater dependent ecosystems**, due to saline intrusion following sea level rise and more frequent and intense hurricanes in the Florida Keys, USA *low / low confidence* [29.3.2.1; (Ross *et al*., 2009; Goodman *et al*., 2012)]	**Shoreline erosion is widespread and increasing on many small islands**, though impact of sea-level rise can presently not be discriminated from climate variability and local disturbance *high / low confidence* [29.3.1.1, 2; (Yamano *et al*., 2007; Cambers, 2009; Novelo-Casanova and Suarez, 2010; Storey and Hunter, 2010; Ford, 2012)] **More frequent inundation in low-lying flood prone areas, increasing appearance of freshwater lenses at surface** *medium / low confidence* [29.3.1.1, 2;(Webb, 2006; Webb, 2007; Yamano *et al*., 2007; Ballu *et al*., 2011)] **Increases in groundwater degradation**, mostly driven by over-pumping or pollution. Limited evidence for saline intrusion due to sea level rise or overtopping *high / low confidence* [29.3.2.2; (White *et al*., 2007a; White *et al*., 2007b; Terry and Falkland, 2010; White and Falkland, 2010)]

Table 18-9: Observed impacts of climate change on human systems across eight major world regions, with confidence in detection / confidence in attribution to climate change stated for each impact. References to related chapters are given as well as key references underlying the assessment.

	Impacts on Human Systems: Health, Food production, Infrastructure and Livelihoods
Africa	**Malaria increases in Kenyan highlands**, partly due to warming *low* / *low confidence* [22.3.5.2, (Prudhomme O'Meara *et al*., 2010; Alonso *et al*., 2011; Stern *et al*., 2011)]
	Reduced productivity of Great Lakes and Lake Kariba, partly due to warming *high* / *low confidence* [23.3.2.2, 23.3.4.4; (Descy and Sarmento, 2008; Hecky *et al*., 2010; Ndebele-Murisa *et al*., 2011; Marshall, 2012)] **Fruit-bearing trees in Sahel decline** *medium* / *medium confidence* (Wezel and Lykke, 2006; Maranz, 2009)
Europe	**Increased allergic sensitization to pollen in Northern Italy** *very low* / *very low confidence* [11.3; (Ariano *et al*., 2010)] **Shift from cold-related mortality to heat-related mortality in England and Wales** *medium* / *low confidence* [18.4.5; (Christidis *et al*., 2010)]
	Stagnation of wheat yields in some countries in recent decades, due to warming and/or drought *high* / *medium confidence* (Brisson *et al*., 2010; Kristensen *et al*., 2011) **Positive yield impacts for wheat, sugar beet and potato in the UK since 1980** *low* / *low confidence* [Fig 7-3; (Gregory and Marshall, 2012)]
Asia	**Negative impacts on aggregate wheat yields in South Asia** *medium*/*low confidence* [Fig.7-3, 7.2.1.1] **Negative impacts on aggregate wheat and maize yields in China** *low* / *low confidence* [Fig.7-3, 7.2.1.1]
	Increases in water-borne diseases have been linked to warming in Israel *low* / *low confidence* (Paz *et al*., 2007)
Australasia	**Wine-grape maturation has advanced in recent decades, partly due to warming** *high* / *medium confidence* (Webb *et al*., 2012)
North America	**Yields of grains, forage, livestock and dairy have declined due to increasing temperatures** unless where accompanied by increased precipitation; soil organic content has declined; salinity has increased; climate change has affected product quality *high* / *low confidence* [26.5.1; (Hayhoe *et al*., 2004; Lin, 2007; Hatfield *et al*., 2008; Wolfe *et al*., 2008; Schlenker and Roberts, 2009; Craine *et al*., 2010)] **Reduced economic returns from agriculture following extreme heat and storms, particularly in Mexico** *high* / *low confidence* [Boxes 26.1, 26.2, 26.4; (Swanson *et al*., 2007; Chen and McCarl, 2009)]
	Direct and indirect economic impacts of climate extremes on industry through reduced supply of raw material, the production process, the transportation of goods, and the demand for certain products *high* / *medium confidence* [26.8; (Lazo *et al*., 2011)] **Damages from climate extremes on infrastructure, especially in the transport and housing sectors** *medium* / *low* confidence [26.8; (Morton *et al*., 2011)] **Impacts of extreme events on economy, lives and livelihoods in urban and rural settlements** *medium* / *low confidence* [26.7.1, 26.7.2; (Kurz *et al*., 2008; MacDonald, 2010)]
Central and South America	**Increase in frequency and extension of dengue fever and yellow fever** *high* / *low confidence* [27.3.7.1; (Teixeira *et al*., 2009; Rodríguez-Morales *et al*., 2010; Jentes *et al*., 2011)]
	Increase in frequency and extension of malaria *high* / *medium confidence* [27.3.7.1; (Rodríguez-Morales *et al*., 2010; Poveda *et al*., 2011)]
	Increase in agricultural yields in Southeastern South America *high* / *medium confidence* [27.3.4.1; (Magrin *et al*., 2007; Barros, 2010)] **Expansion of agricultural areas in climatically marginal regions of Argentina** *high* / *low confidence* [27.3.4; (Barros, 2010; Hoyos *et al*., 2012)] **Reduction in fish stocks (Peru, Colombia, Brazil)** *low* / *very low confidence* [27.3.7.1; (Allison *et al*., 2009; Freire and Pauly, 2010)]
Polar Regions	**Impact on livelihoods of high Arctic indigenous peoples** *medium* / *medium confidence* [18.4.5, Box 18-5; (Ford *et al*., 2009; Beaumier and Ford, 2010; Pearce *et al*., 2010)]

Small Islands	**Degradation of coastal fisheries** *high* / *low confidence* [29.3.3; 18.4.5; 30.4, 6.3.2] **Casualties and damage from extreme weather events** *very high* / *very low confidence* [29.3.3]

Table 18-10: Reported confidence of detection of observed changes in "Unique and Threatened Systems" and attribution of observed changes to observed climate change. Assessments are for global or the indicated regional domain, with regional variations indicated in the final column.

Impact on unique or threatened system	**Source for overarching assessment**	**Confidence in**		**Regional details, with corresponding subsections and confidence in detection/confidence in attribution**
		detection	**attribution**	
Shrinking / receding glaciers	18.3.1	*very high*	*high*	Tropical Highland Glaciers, East Africa (22.5.1): *very high* / *medium* European Alps: *very high* / *high* Asia (24.4.2.2): *high* / *medium* New Zealand (Table 25-1): *high* / *low* North America: *high* / *high* Andean tropical glaciers and extra tropical icefields (27.3.1.1): *high* / *high* Polar glaciers: *high* / *high*
Mountain and lowland permafrost degradation	18.3.1.2	*high*	*medium*	Europe: *medium* / *medium* Siberia, Central Asia and Tibetan Plateau (24.4.2.2): *high* / *high* North America: *medium* / *medium* Southern Arctic (28.2.1.1): *high* / *high*
Arctic coastal permafrost degradation	18.3.1.2, 24.4.3.2, 28.2.1.1	*high*	*high*	
Warm water reef building corals – increased mortality and bleaching	5.3.1.6, 6.3.2.1.2, 30.3.1.1, 30.5, 30.8.2, Box 18-3	*very high*	*high*	Asia (24.4.3.2): *high* / *high* Australian Great Barrier Reef: *high* / *high* Western Caribbean (27.3.3.1): *very high* / *high* Coastal reefs surrounding small islands (29.3.1): *high* / *high*
Shrub increase and permafrost decay in Arctic tundra¸ onset of biome shift	18.3.2.4, 28.2.3.2	*high*	*high*	
Increased tree mortality in the Amazon; onset of biome shift	4.3.3	*low*	*very low*	
Increased tree mortality in boreal forests; onset of biome shift	4.3.3	*low*	*low*	
Changes in Arctic marine ecosystems	18.5.7, 28.2.2.1	*high*	*medium*	
Decline in extent of mangroves and coastal wetlands	27.3.3.1, 29.3.1.4	*very high*	*very low*	Mangrove degradation northern South American coast (27.3.3.1): *high* / *low* Impacts on mangroves and sea grasses in coastal areas of small islands (29.3.1.4): *high* / *low*
Livelihood impacts on indigenous Arctic peoples	18.4.7, Box 18-5	*medium*	*medium*	

Table 18-11a: Confidence in detection of changes in extreme weather hazard and attribution of a major role of changing greenhouse gas concentrations in the observed changes.

Observed changes in extreme weather or hydrologic hazard	**Confidence in**		**Assessment***
	detection	**attribution**	
Increasing frequency and intensity of extreme hot events	*high*	*high*	WGI AR5 Chapter 10.6.1
Decreasing frequency and intensity of extreme cold events	*high*	*high*	WGI AR5 Chapter 10.6.1
Increases in the number and intensity of heavy precipitation events	*medium*	*medium*	WGI AR5 Chapter 10.6.1
Increases in tropical cyclone activity	*low*	*low*	WGI AR5 Chapter 10.6.1
Changes in tornadoes or hail	*very low*	*very low*	Chapter 10.6.1
More intense and longer dry spells in some low and mid latitude regions	*low*	*low*	WGI AR5 Chapter 10.6.1
Changes in inland flood magnitude and frequency	*low*	*low*	3.2.3, 18.3.1.1
Increasingly frequent coastal flooding	*medium*	*low*	29.3.1.1, 29.3.2.2, 5.3.3.3

*more detailed regional information consistent with AR5 WGI Chapter 10 assessment can be found in Seneviratne *et al*. (2012)

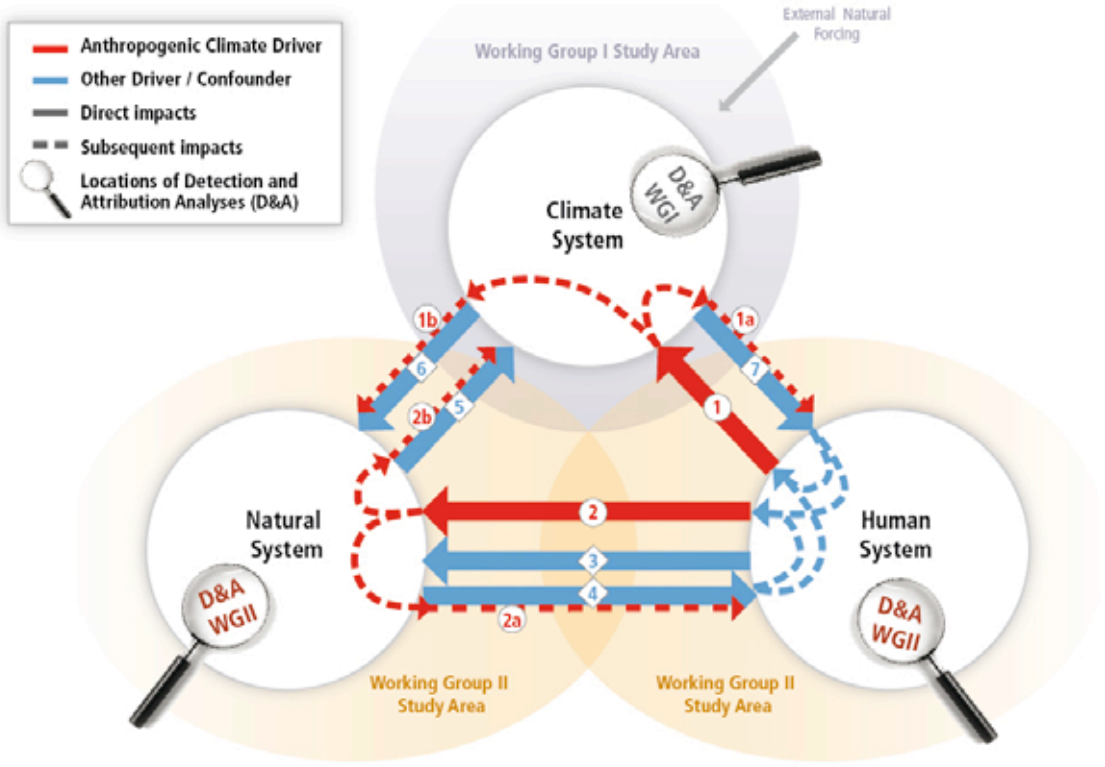
Table 18-11b: Confidence in detection of observed trends in damage in various systems and attribution of a major role of observed changes in extreme weather to those observed trends.

Observed changes in impacts of extreme weather	**Relevant weather extremes**	**Confidence in**		**Assessment**
		detection	**attribution**	
Increased coral bleaching	Hot surface waters	*very high*	*high*	5.3.1.6, 6.3.2, Box 18-3, 24.4.3.2, 27.3.3.1, 29.3.1, 30.3.1.1, 30.5. 30.8.2
Increased beach erosion in low and mid latitudes	High storm waves and surges	*high*	*very low*	5.3.1.2
Increased erosion of Arctic coastal bluffs	Lack of sea ice protection from wind storms	*high*	*high*	24.4.3.2, 28.2, 28.3.4
Increased South American landslide frequency	Heavy precipitation	*medium*	*low*	27.2.1.1
Cascading food web effects on Arctic grazers and predators	Higher frequency of rain-on-snow events	*high*	*high*	28.2.1.1
Increased drought in high Arctic deserts	Warm spells	*high*	*high*	28.2.1.1
Increased monetary losses due to extreme weather events	Storms, floods	*very high*	*very low*	10.7, 18.4.4.2

Table 18-12: Confidence in detection of impacts on aggregate impact measures and confidence in attribution of at least a minor role of climate change in those observed changes.

Global aggregated impact measure	**Reference chapters**	**Confidence in**	
		detection	**attribution**
Glacier ice volume reduction	18.3.1.3; 3.2.2	*very high*	*high*
Shift of permafrost boundary to higher altitudes and latitudes, and increase of active layer thickness	18.3.1.3	*high*	*medium*
Increase in terrestrial net primary production and C stocks	18.3.2.2	*high*	*low*
Negative yield impacts on global wheat against trends in technology, practice, and coverage	18.4.1.1, Fig 7-3	*very low*	*very low*
Negative yield impacts on global maize against trends in technology, practice, and coverage	18.4.1.1, Fig 7-3	*low*	*low*
Small increase in marine net primary production	Table 18-1	*medium*	*low*
Change in fishery productivity	Table 18-2; Fig 30.14, 6.6.1	*high*	*low*
Increase in monetary losses due to extreme weather	18.4.4.2 and 10.7	*very high*	*very low*

Figure 18-1: Schematic of the subject covered in this chapter. The Earth system can be divided into three broad interacting systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone *et al*. (2013).



	Example of Drivers	Example of Impacts	
		Direct impacts	Subsequent impacts
1 1a 1b	Emission of CO_2	Warming	 Altered crop yield Shift in species phenology
2 2a 2b	Emission of CO_2	Carbon fertilization of plants	 Increase in forestry yield Change in humidity
3	Pollution of river catchment	Decrease in fisheries	
4	Plague of crop pests	Decrease in crop yield	
5	Forest fire	Increased windiness	
6	El Nino event	More wildfires	
7	El Nino event	Fisheries	

Figure 18-2: A schematic diagram comparing approaches to attribution for an ecological system. The multi-step approach differs from the single-step approach in having a discontinuity between the attributed climate change and the observed weather driving the ecological model. Adapted from Stone *et al*. (2013).

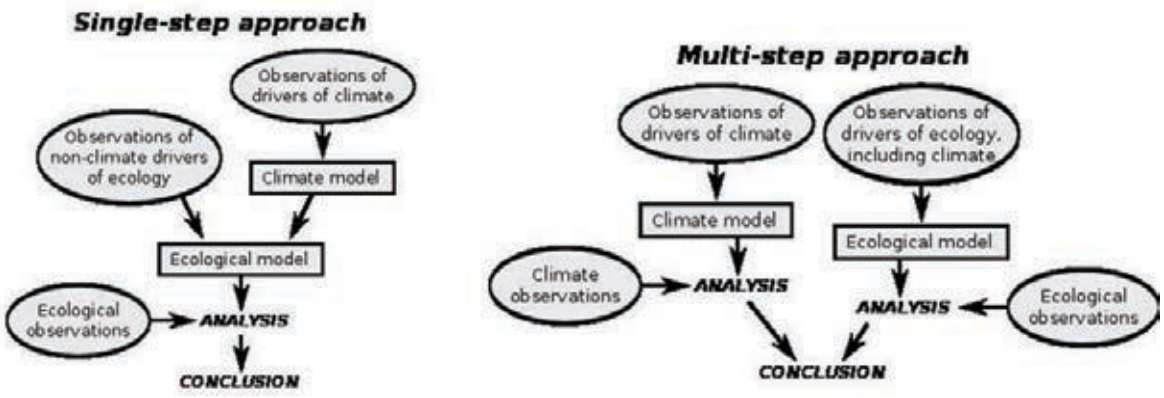


Figure 18-3: Levels of confidence in detection and attribution of observed climate change impacts for freshwater systems over the past several decades, based on expert assessment contained in this section 18.3.1 and augmented by subsections of chapter 3 as indicated. Numbered symbols refer to: Freshwater systems (18.3.1.1): 1 groundwater depletion (Ch.3.2.4), 2 changing river flow (Ch. 3.2.3), 3 changing flood frequency or intensity (Ch. 3.2.3), 4 reduction in lake and river ice duration or thickness (Ch. 18.3.1.2); Cryosphere: 5 shrinking glaciers (Ch. 3.2.2, 18.3.1.2), 6 changes in glacier lakes (Ch. 18.3.1.1), 7 erosion and degradation of arctic coastal permafrost (Ch. 18.3.1.2), 8 degradation and thaw of lowland and mountain permafrost (Ch. 18.3.1.2), Soils and rock (18.3.1.3): 9 Increasing erosion (Ch.3.2.6), 10 changes in shallow landslides (Ch.3.2.6), 11 increasing frequency of Alpine rock failures

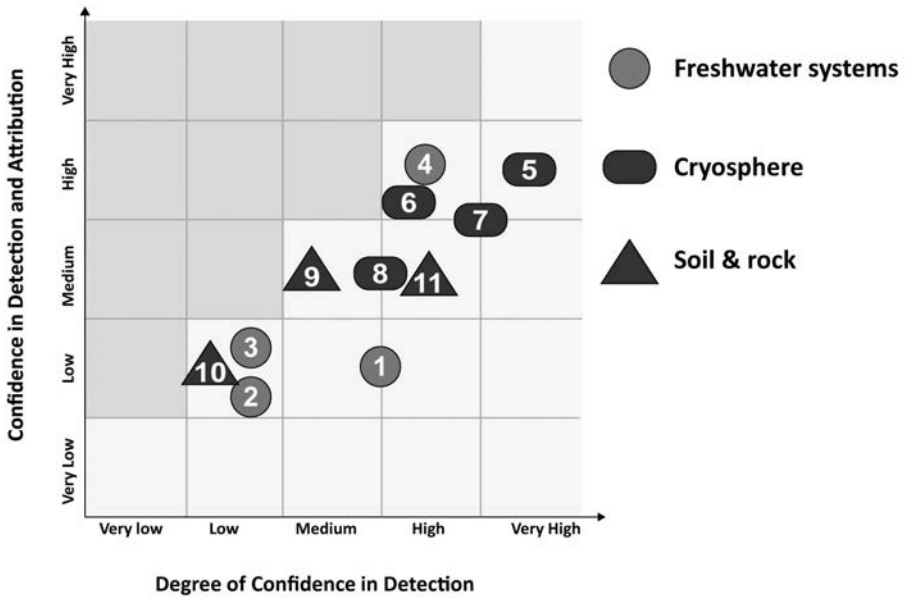


Figure 18-4: Confidence in detection and attribution of observed impacts on unique and threatened systems as a result of recent climate change. Assessments are for confidence in detection of a change and for confidence in attribution of a major role of observed climate change. Large letters denote conclusions for the full-scale system, while small letters denote conclusions for regional subsets of the systems. System changes include shrinking / receding glaciers, mountain and lowland permafrost degradation, Arctic coastal permafrost degradation, increased mortality and bleaching of warm water reef-building corals, increased shrub cover and permafrost decay in the northern tundra, increased tree mortality in the Amazon, increased tree mortality in boreal forests, changes in Arctic marine ecosystems, decline in extent of mangroves and coastal wetlands, and impacts on livelihoods of indigenous Arctic peoples. See Table 18-10 for details and references.

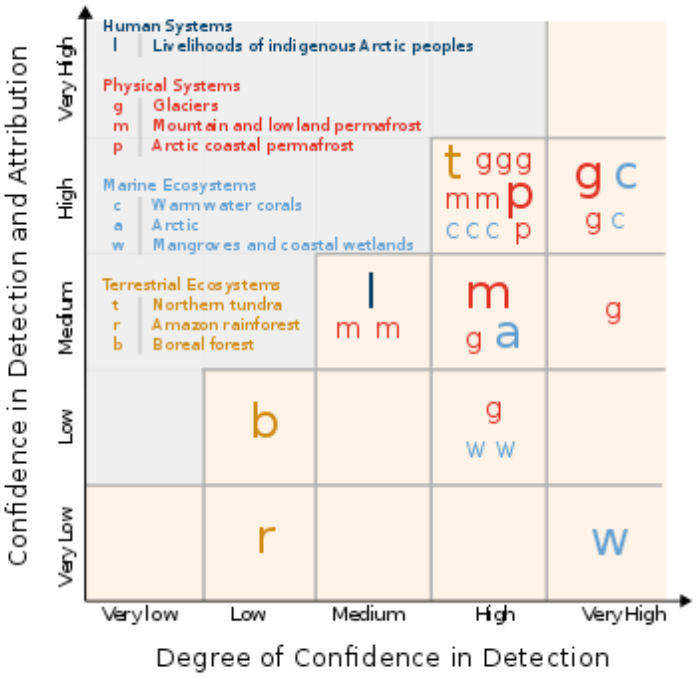
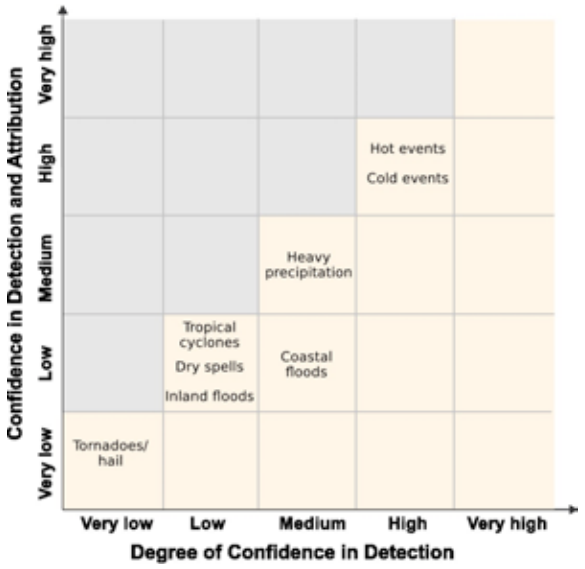


Figure 18-5: Left: confidence in detection of observed changes in extreme weather hazards and attribution of a major role of changing greenhouse gas concentrations in the observed changes. Right: confidence in detection of observed changes in damages related to extreme weather and attribution of major role to observed changes in extreme weather.



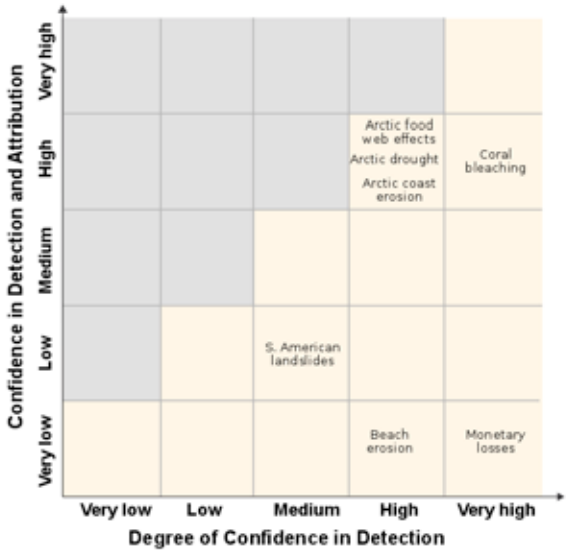
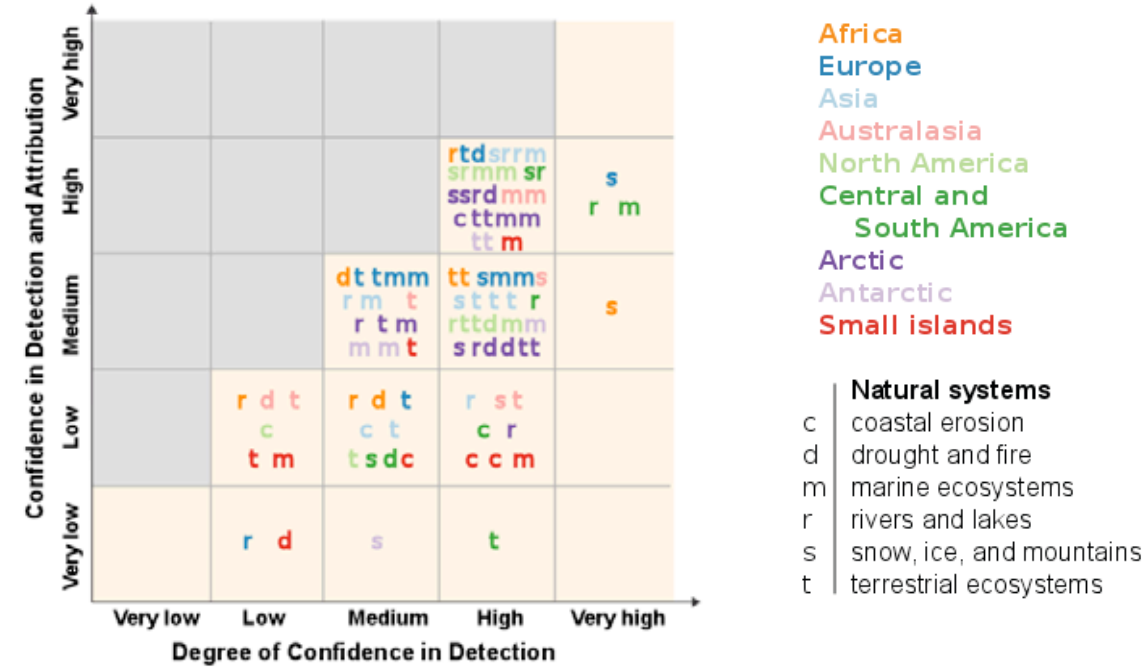
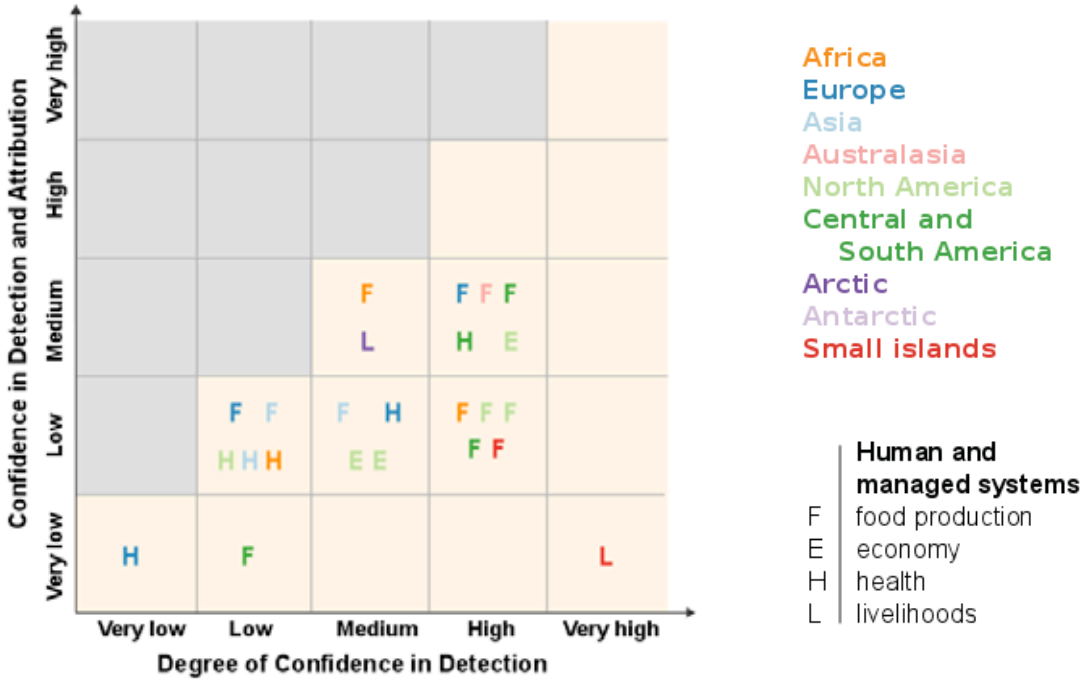


Figure 18-6: Confidence in detection of observed changes in natural systems (panel a) and human and managed systems (panel b) across regions, and confidence in attribution of such trends to observed climate change. Based on assessments developed in Tables 18-6 through 18-9.

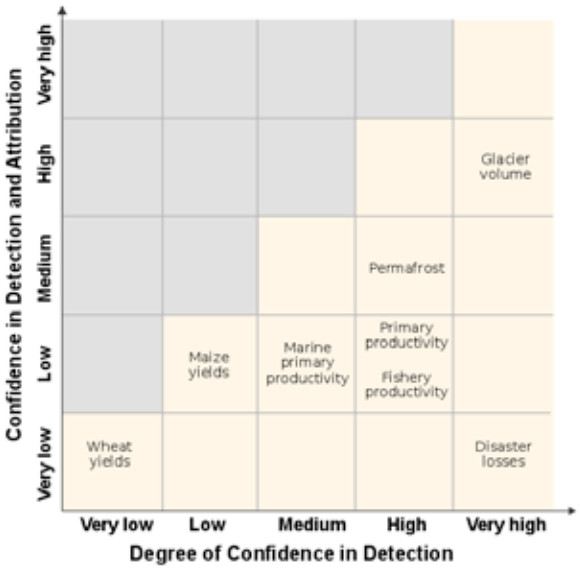


Panel a: Regional Impacts on Natural Systems



Panel b: Regional Impacts on Human Systems

Figure 18-7: Confidence in detection of changes in aggregate impact measures and attribution of at least a minor role of climate change in those trends



Chapter 19. Emergent Risks and Key Vulnerabilities

Coordinating Lead Authors
Michael Oppenheimer (USA), Maximiliano Campos (Costa Rica), Rachel Warren (UK)

Lead Authors
Joern Birkmann (Germany), George Luber (USA), Brian O'Neill (USA), Kiyoshi Takahashi (Japan)

Contributing Authors
Franz Berkhout (Netherlands), Pauline Dube (Botswana), Wendy Foden (South Africa), Stefan Greiving (Germany), Solomon Hsiang (USA), Matt Johnston (USA), Klaus Keller (USA), Joan Kleypas (USA), Robert Kopp (USA), Rachel Licker (USA), Carlos Peres (UK), Jeff Price (UK), Alan Robock (USA), Wolfram Schlenker (USA), John Richard Stepp (USA), Richard Tol (UK), Detlef van Vuuren (Netherlands)

Review Editors
Mike Brklacich (Canada), Sergey Semenov (Russian Federation)

Chapter Scientist
Rachel Licker (USA)

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Executive Summary

This chapter assesses the interaction of changing physical characteristics of the climate system with evolving characteristics of human, socioeconomic, and biological systems (exposure and vulnerability) to produce risk [19.2], in relation to Article 2 of the UN Framework Convention on Climate Change. Alternative development paths influence risk by changing both the likelihood of physical impacts (through their effects on greenhouse gas emissions) and by altering vulnerability and exposure [19.2.4, Figure 19-1].

A particular focus is placed on interactions among climate change impacts in various sectors and regions, and human vulnerability and adaptation in other sectors and regions, as well as interactions between adaptation and mitigation actions. Such interactions are generally not included, or not well integrated, into projections of climate change impacts, but their consideration leads to the identification of a variety of *emergent risks* that were not previously recognized. This chapter identifies several such complex-system interactions that increase vulnerability and risk [19.3, *high confidence*]. For example:

- The risk of severe harm and loss due to climate change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones. These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure, generating new systemic risk [19.3.2.4].
- The risk of climate change to human systems is increased by the loss of ecosystem services (e.g. water and air purification, protection from extreme weather events, preservation of soils, recycling of nutrients, and pollination of crops), which are supported by biodiversity [19.3.2.1, *high confidence*].
- In some water stressed regions, groundwater stores that have historically acted as buffers against climate change impacts are being depleted, with adverse consequences for human systems and ecosystems, whilst at the same time climate change may directly increase or decrease regional groundwater resources [19.3.2.2, *high confidence*].
- Climate change adversely affects human health, increasing exposure and vulnerability to a variety of other stresses, for example by altering the prevalence and distribution of diseases that are weather and climate sensitive, increasing injuries and fatalities resulting from extreme weather events, and eroding mental health in response to population displacement [19.3.2.3, *high confidence*].
- Spatial convergence of impacts in different sectors creates impact 'hotspots' involving new interactions (*high confidence*). Examples include the Arctic (where sea ice loss and thawing disrupts transportation, buildings, other infrastructure, and potentially disrupts Inuit culture); the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification); and Sub-Saharan Africa (where global warming at the high end of the range projected for this century, i.e., more than 4°C above preindustrial levels, would be especially disruptive, resulting in high risk of reduced extent of croplands, reduced length of the growing season, increased hunger, and increased malaria transmission) [19.3.2.4].
- Adaptation designed for one sector may interfere with the functioning of another sector, creating new risks (*high confidence*). For example, increasing crop irrigation in response to a drying climate can exacerbate water stress in downstream wetlands, where the latter otherwise provide important water cleaning services [19.3.2.5].

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change, sometimes mediated by the adaptive responses of human populations [19.4, *high confidence*]. Responses to climate change can result from localized impacts that generate distant harm via responses transmitted through human or ecological systems.

- Increasing prices of food commodities on the global market due to local climate impacts, sometimes in conjunction with demand for biofuels, decrease food security and exacerbate malnutrition at distant locations [19.4.1].
- Climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*) [19.4.2.1].
- The possibility that climate change will alter patterns of violence is a risk emerging in the literature. The effect of climate change on conflict and insecurity has the potential to become a key risk because the reported magnitude of the influence of the climate's variability on security is large [19.4.2.2].
- Shifting species ranges in response to climate change adversely affect ecosystem function and services while presenting new challenges to conservation efforts [19.4.2.3]. Where range shifts cannot track climatic changes, species are at risk of eventual extinction (*high confidence*).

Additional risks have emerged recently in the literature related to particular biophysical impacts of climate change [19.5, *high confidence*]. These include decreasing viability of marine calcifying organisms due to ocean

acidification [19.5.2]; increasing production and allergenicity of pollen and allergenic compounds as well as decreasing nutritional quality of key food crops due to high ambient concentrations of CO_2 [19.5.3]; and the risk of adverse regional impacts arising from Solar Radiation Management implemented for the purposes of limiting global warming [19.5.4].

Consequences of global temperature rise in excess of 4°C relative to preindustrial levels can now be assessed [19.5.1]. Key risks associated with large temperature rise include exceedance of human physiological limits in some locations and nonlinear earth system responses *(high confidence)*. There may also be key risks in other sectors and regions that have not been studied in this context.

Global and local socio-economic, environmental and governance trends confirm that vulnerability and exposure of communities or social-ecological systems to climatic hazards are dynamic and thus varying across temporal and spatial scales. Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socio-economic development pathways and the vulnerability and exposure of people. Changes in poverty or socio-economic status, race and ethnicity compositions as well as age structures and changes in governance had a significant influence on the outcome of past crises associated with climatic hazards [19.6.1.3].

Challenges for vulnerability reduction and adaptation are particularly high in regions that have shown severe difficulties in governance. Studies confirm that countries that are classified as failed states and affected by violence are often not able to effectively reduce vulnerability. There is *high confidence* that unless governance improves in countries with severe governance failure, an increase in risk is to be expected as a result of climate changes interacting with increased human vulnerability [19.6.1.3.3].

Assessment of existing frameworks pertinent to Article 2 of the UNFCCC, based on Key Risks, Key Vulnerabilities, and Reasons for Concern, has led to evaluations of risk being updated in light of the advances since AR4, including SREX and the current report's discussions of vulnerability, human security, and adaptation, [19.6.3].

Several *key risks* resulting from the interaction of hazardous climate changes and physical impacts with the vulnerability of societies and exposed systems were identified in this chapter [19.6.2.1.].

- The risk for increased food insecurity can result from both local conditions like adverse changes in rainfall patterns and a lack of alternative sources of income for some affected households, as well as regional and national conditions like a breakdown of food distribution and storage processes [*high confidence*].
- The risks of dispossession of land – including the alteration of rural inhabitants' coping and adaptation processes - results from shifts in energy policies and global markets.
- A high risk of loss of livelihoods due to changes in climatic conditions and socioeconomic structures affecting people living in low-laying costal zones and people engaged in rain-fed agriculture in developing countries and countries with economies in transition [*high confidence*].
- The risks of increasing morbidity, mortality, and infrastructure failure as well as new systemic risks (such as the risk of heat stress as a result of power shortages during extreme events) in urban areas in both developed and developing countries [*high confidence*].
- The risk of increase in disease burden resulting from the interaction of changes in physical climate conditions like increasing temperatures with the vulnerability of people due to, for example, an aging population.

The determination of key risks as reflected, for example, in the Reasons for Concern did not previously distinguish between alternative development pathways. The development of risk profiles from Shared Socioeconomic Pathways and Representative Concentration Pathways is an important area of research that can lead to improvement in the framework developed in this chapter [19.6.3.1].

Updating of the Reasons for Concern leads to the following assessment:

- **Unique human and natural systems tend to have very limited adaptive capacity, and hence we have *high confidence* that climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C over preindustrial levels were exceeded.** In addition, there is new

and stronger evidence to support the previous judgment of *high confidence* that a warming of up to 2°C above 1990-2000 levels would result in significant impacts on many unique and vulnerable systems, and would likely increase the endangered status of many threatened species, with increasing adverse impacts and increasing risk of extinctions (and increasing confidence in this conclusion) at higher temperatures [19.6.3.2].

- **The overall risk from extreme events due to climate change has not changed significantly since AR4 but there is higher confidence in the attribution of some types of extreme events to human activity and in the assessment of the risk from extreme events in the coming decades.** In addition, there is a new appreciation for the importance of exposure and vulnerability, in both developed and developing countries [19.6.3.3], in assessing risk associated with extreme events. Many of the key vulnerabilities, key risks, and emergent risks identified in individual chapters of this report reflect differential vulnerability between groups due to, for example, age, wealth, or income status, and deficiencies in governance [19.6.1], which are particularly important in assessing this Reason for Concern and also the following one associated with the distribution of impacts.
- **Risk associated with the distribution of impacts is generally greatest in low-latitude, less developed areas, but because vulnerability is unevenly distributed within countries, some populations in developed countries are highly vulnerable to warming of less than 2°C, as noted in AR4 (*high confidence*) [19.6.3.4].**
- **Globally aggregated risk is underestimated because it does not include many non-monetized impacts, such as biodiversity loss, and because it omits many known impacts that have only recently be quantified, such as reduced labor productivity [19.6.3.5, *high confidence*]. In addition, aggregated estimates of costs mask significant differences in impacts across sectors, regions, countries and populations [19.6.3.5, *very high confidence*].** The overall assessment of aggregate risk and confidence in that assessment has not changed since AR4.
- **The risk associated with large-scale singular events such as the at least partial deglaciation of the Greenland ice sheet remains comparable to that assessed in AR4 [19.6.3.6].**

The management of key and emergent risks of climate change and Reasons for Concern includes (i) mitigation that reduces the likelihood of physical impacts and (ii) adaptation that reduces the vulnerability and exposure of societies and ecosystems to those impacts [19.7]. Advances in the assessment and implementation of mitigation measures and adaptation strategies include for the first time evaluation of avoided damages from a range of strategies.

Impacts of climate change avoided under a range of scenarios for mitigation of greenhouse gas emissions are potentially large and increasing over the 21st century [19.7.1, *high confidence*]. Among the impacts assessed here, benefits from mitigation are most immediate for ocean acidification and least immediate for impacts related to sea level rise. Since mitigation reduces the rate as well as the magnitude of warming, it also delays the need to adapt to a particular level of climate change impacts, potentially by several decades.

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). For example, no model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood and recent findings suggest that comprehensive adaptation to current climate risk is prohibitively expensive, indicating that adaptions to future changes are similarly constrained [19.7.2.1]. Assessments of stringent mitigation scenarios suggest that they can potentially avoid one half of the aggregate economic impacts that would otherwise accrue by 2100, and between 20-60% of the physical impacts, depending on sector and region [19.7.1].

The design of risk-management strategies could be informed by observation and projection systems that provide an actionable early warning signal of an approaching threshold response. However, there is *low confidence* in the feasibility and requirements for such systems, since studies to date are highly simplified and limited in number [19.7.3].

The risk of crossing tipping points in socio-ecological systems may be reduced by preserving ecosystem services (*medium confidence*). Tipping points are thresholds beyond which adverse impacts increase non-linearly.

Some tipping points may be avoided by limiting the level of climate change and/or removing concomitant stresses such as overgrazing, overfishing, and pollution [19.7.4] but there is *low confidence* in location of such tipping points and measures to avoid them.

19.1. Purpose, Scope, and Structure of the Chapter

The objective of this chapter is to assess new literature published since the Fourth Assessment Report on emergent risks and key vulnerabilities to climate change from the perspective of the distribution of risk over geographic location, economic sector, time period, and socioeconomic characteristics of individuals and societies. Frameworks used in previous IPCC reports to assess risk in the context of Article 2 of the UN Framework Convention on Climate Change (UNFCCC) are updated and extended in light of new literature; and additional frameworks arising in recent literature are examined. A focal point of this chapter is the interaction of the changing physical characteristics of the climate system with evolving characteristics of socioeconomic and biological systems (exposure and vulnerability) to produce risk (see Figure 19-1).

[INSERT FIGURE 19-1 HERE
Figure 19-1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. It underscores that risks are a product of a complex interaction between physical hazards associated with climate change and climate variability on the one hand, and the vulnerability of a society or a social-ecological system and its exposure to climate-related hazards on the other. The definition and use of "key" are indicated in Box 19-2 and the glossary. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions. Both the changes in the climate system (left side) and the development processes (right side) are key drivers of the different core components (vulnerability, exposure, and physical hazards) that constitute risk (modified version of Figure 1, IPCC, 2012).]

19.1.1. Historical Development of this Chapter

The Third and Fourth Assessment Reports (TAR and AR4, respectively) each devoted chapters to evaluating the state of knowledge relevant to Article 2 of the UNFCCC (Smith *et al*., 2001; Schneider *et al*., 2007; see Box 19-1). The TAR sorted and aggregated impacts discussed in the literature according to a framework called *Reasons for Concern* (RFCs), and assessed the level of risk associated with individual impacts of climate change as well as each category or "reason" as a whole, generally as a function of global mean warming. This assessment took account of the distribution of vulnerability across particular regions, countries, and sectors. AR4 furthered the discussion relevant to Article 2 by assessing new literature and developing criteria potentially useful for policy makers in the determination of *key* impacts and vulnerabilities, i.e, meriting particular attention in respect to Article 2 (see Box 19-2 for definitions of Reasons for Concern and Key Vulnerabilities [KVs]). AR4 emphasized the differences in vulnerability between developed and developing countries but also assessed emerging literature describing vulnerability pertaining to various aggregations of people (such as by ethnic, cultural, age, gender, or income status) and response strategies for avoiding key impacts. The Reasons for Concern were updated and the Synthesis Report (IPCC, 2007) noted that they "remain a viable framework to consider key vulnerabilities". However, their utility was limited by several factors: the lack of a time dimension (i.e., representation of impacts arising from timing and rates of climate change and climate forcing), the focus on risk only as a function of global mean temperature, lack of a clear distinction between impacts and vulnerability, and importantly, incomplete incorporation of the evolving socioeconomic context, particularly adaptation capacity, in representing impacts and vulnerability.

19.1.2. The Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

SREX (IPCC, 2012) provides additional insights with respect to one RFC (the risk of extreme weather events) and particularly the distribution of capacities to adapt to such events between countries, communities, and other groups,

and the limitations of implementation of these capacities. SREX emphasized the role of the socioeconomic setting and development pathway (expressed through exposure and vulnerability) in determining, on the one hand, the circumstances where extreme events do or do not result in extreme impacts and disasters, and on the other hand, when non-extreme events may also result in extreme impacts and disasters.

19.1.3. New Developments in this Chapter

With these frameworks already established, and a long list of impacts and key vulnerabilities enumerated and categorized in previous assessments, the current chapter has three goals: first, to recognize the dynamic nature of our understanding by assessing *emergent and emerging risks* (see Box 19-2, Table 19-3). These risks are, respectively, those which arise out of complex interactions involving climate and socioecological systems, and those which have only recently emerged in the scientific literature in sufficient detail to permit assessment. In this chapter, we consider only those emergent and emerging risks which have the potential to become relevant to interpreting Article 2 as additional understanding accumulates. For example, since AR4, sufficient literature has emerged to allow initial assessment of the relationship between climate change and conflict. The second goal is to reassess and reorganize the existing frameworks (based on Reasons for Concern and Key Vulnerabilities) for evaluating the literature pertinent to Article 2 of the UNFCCC in order to address the deficiencies cited in section 19.1.1, particularly in light of the advances in SREX and the current report's discussions of vulnerability and human security (see chapters 12 and 13) and adaptation (see chapters 14-17 and 20). From this perspective, the objective stated in Article 2 may be viewed as aiming in part to ensure human security in the face of climate change. Thirdly, this chapter will assess recent literature pertinent to additional frameworks for categorizing risk and vulnerability, particularly focusing on indirect impacts and interaction and concatenation of risk, including geographic "hotspots" (see 19.3).

In order to clarify the relative roles of characteristics of the physical climate system, like increases in temperature, precipitation, or storm frequency, and characteristics of the socioeconomic and biological systems with which these interact (vulnerability and exposure) to produce risks of particular consequences (used interchangeably here with "impacts" and "outcomes"), we rely heavily on a concept used sparingly in the TAR and AR4, *key risks* (see Box 19-2). Furthermore, we emphasize recent literature pointing to the *dynamic* character of vulnerability based on its intimate relationship to development.

We consider a variety of types of emergent risks, including for example, vulnerability to impacts arising from multiple interacting systems and stresses, indirect impacts, trans-boundary impacts, and impacts occurring at a long distance from the location of the climate change which causes them (Oppenheimer, 2012). One example which illustrates all of these properties is the extent to which climate change impacts on agriculture, water resources, and sea level affect migration flows. These shifts entail both risks and potential benefits for the migrants, for the regions where they originate, and for the destination regions (see 19.5.2.1 and 12.4). Risks include indirect impacts, like the effect of land use changes on ecosystems, occurring at the new locations of settlement, which may be near the location of the original climate impact or quite distant. Such distant, indirect effects would compound the direct consequences of climate change at the locations receiving the incoming migrants.

_____ START BOX 19-1 HERE ____

Box 19-1. Article 2 of the UNFCCC and the Copenhagen Accord

Article 2

OBJECTIVE
The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Copenhagen Accord (excerpt)

To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change.

_____ END BOX 19-1 HERE ____

____ START BOX 19-2 HERE ____

Box 19-2. Definitions

Vulnerability - The propensity or predisposition to be adversely affected. A broad set of factors such as wealth, social status, and gender determine vulnerability and exposure to climate-related risk.

Exposure - The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected.

Impacts - Effects on natural and human systems. In this chapter, the term is used to refer to the effects on natural and human systems of hazardous physical events, of disasters, and of climate change. Impacts are also referred to as *consequences* and *outcomes*. They are a function of exposure and vulnerability, and generally refer to adverse effects on lives, livelihoods, health status, ecosystems, economic, social and cultural assets, services (including environmental), and infrastructure due to the interaction of hazardous events or trends occurring within a specific time period and the vulnerability of a society or system exposed. We refer to the effects of climate changes on geophysical systems, such as floods, droughts, and sea level rise, as *physical impacts*.

Hazard - The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. In this chapter, hazard usually refers to climate-related events or trends or their physical impacts.

Stressors - Those events and trends which are not-climate-related but have an important effect on the system exposed and can increase vulnerability to climate-related risk.

Risk - The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk is often represented as probability of occurrence of a hazardous event(s) multiplied by the consequences if the event(s) occurs.

Risk = Probability of Event(s) X Consequences

This report assesses climate-related risks.

Key vulnerability, key risk, key impact - A vulnerability, risk, or impact relevant to the definition and elaboration of "dangerous anthropogenic interference (DAI) with the climate system," in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policy makers in that context.

Key risks are potential adverse consequences for humans and social-ecological systems due to the interaction of hazardous climate changes and physical impacts with vulnerabilities of societies and systems exposed. Risks are not considered "key" due to high physical impact alone, absent significant vulnerability and exposure.

Vulnerabilities are considered "key" if they have the potential to combine with climate changes and physical impacts to result in severe consequences for society or social-ecological systems. Vulnerabilities that have little influence on risk would not be considered key.

Extract from Chapter 19, WGII, AR4:

Many impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them 'key'. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system, in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19-1). Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgments informed by the state of scientific knowledge.

***Emergent Risk*:** A risk that arises from the interaction of phenomena in a complex system, for example the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability in the receiving region.

***Emerging Risk*:** A risk that has emerged only recently in the scientific literature in sufficient detail to permit assessment. For example, the initial consequences associated with these risks may have only recently been detected above the natural variability of the climate system, as is the case for certain effects of ocean acidification on calcareous organisms. For clarity, where these emerging risks arise from the interaction of phenomena in a complex system (and are thus also emergent risks) they are discussed in sections 19.3 and 19.4 relating to emergent risks.

In this chapter, the only emergent and emerging risks discussed are those which have the potential to become key risks once sufficient understanding accumulates.

Reasons for Concern – Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be "dangerous" (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

Summary of Reasons for Concern (updated from TAR, WGII, Chapter 19):

"Reasons for Concern" may aid readers in making their own determination about what is a "dangerous" climate change. Each reason for concern is consistent with a paradigm that can be used by itself or in combination with other paradigms to help determine what level of climate change is dangerous. The reasons for concerns are the relations between global mean temperature increase and:

1. Risks to unique and threatened systems
2. Risks associated with extreme weather events
3. Risks associated with the distribution of impacts
4. Risks associated with aggregate impacts
5. Risks associated with large-scale singular events

_____ END BOX 19-2 HERE _____

19.2. Framework for Identifying Key Vulnerabilities, Key Risks, and Emergent and Emerging Risks

19.2.1. Risk and Vulnerability

Definitions and frameworks that systematize physical impacts, exposure, vulnerability, risk and adaptation in the context of climate change are multiple, overlapping, and often contested (see e.g. Burton *et al.*, 1983; Blaikie *et al.*, 1994; Twigg, 2001; Turner *et al.*, 2003a; Turner *et al.*, 2003b; UN/ISDR, 2004; Schröter, 2005; Füssel and Klein, 2006; Adger, 2006; Villagrán de León, 2006; Thomalla *et al.*, 2006; Tol and Yohe, 2006; Birkmann, 2006b; IPCC,

2007; Cutter *et al*., 2008; Cutter and Finch, 2008; ICSU - LAC, 2010a; ICSU - LAC, 2010b; Cardona, 2011; Kienberger, 2012; IPCC, 2012; Costa and Kropp, 2012; Birkmann *et al*., 2013); however, most of the concepts and the respective literature differentiates between vulnerability, risk, impacts and hazards (see e.g. Hutton *et al*., 2011; IPCC, 2012; Birkmann *et al*., 2013). The following section serves not solely as an update of existing knowledge about key vulnerabilities and key risks since the AR4, but also provides a more coherent framework to systematize these concepts and to enhance the understanding of these phenomena based on new literature, including SREX (IPCC, 2012).

The large body of literature (see above) underscores that risks to climate change are not solely externally generated circumstances to which societies respond, but rather, the results of complex interactions among societies or communities, ecosystems, and physical impacts arising from climate change (Susman *et al*., 1983; Comfort *et al*., 1999; Birkmann *et al*., 2011; UNISDR, 2011; IPCC, 2012b; Birkmann *et al*., 2013). We refer to the effects of climate changes on geophysical systems, such as floods, droughts, deglaciation, and sea level rise, as *physical impacts*. In contrast, vulnerability refers primarily to characteristics of human or social-ecological systems exposed to hazardous climatic or non-climatic events and trends (UNDRO, 1980; Liverman, 1990; Cannon, 1994; Blaikie *et al*., 1996; UN/ISDR, 2004; Cannon, 2006; Birkmann, 2006; Cannon, 2006; Thywissen, 2006; Füssel and Klein, 2006; IPCC, 2012). Ecosystems or geographic areas can be classified as vulnerable, and merit particular attention if vulnerability of humans arises from impacts on the related ecosystem services. The Millennium Ecosystem Assessment (MEA) for example identified ecosystem services that affect the vulnerability of societies and communities, such as provision of fresh water resources and air quality (MEA, 2005)

Compared to the AR4 which did not fully differentiate key vulnerabilities, impacts and risks, the new conceptualization used here provides a more coherent and precise systematization (see Figure 19-1). In addition, the framework underscores that the development process of a society has significant implications for vulnerability and risk. Climate change is not a risk per se; rather climate changes and related physical impacts interact with the vulnerability of exposed systems to determine the level of risk (see Table 19-3). Identifying key vulnerabilities facilitates estimating key risks when coupled with information about the climate and climate change. The new differentiation provides the basis for criteria developed in this chapter for assessing vulnerability and risk.

19.2.2. Criteria for Identifying Key Vulnerabilities and Key Risks

Vulnerability is dynamic and context specific, determined by human behavior and societal organization, which influences for example the susceptibility of people (e.g. by marginalization) and their coping and adaptive capacities to hazardous events and trends (see IPCC, 2012). In this regard coping mainly refers to capacities that allow a system to protect itself in the face of adverse consequences, while adaptation – by contrast – denotes a longer-term process that also involves adjustments in the system itself and refers to learning, experimentation and change (Yohe and Tol, 2002; Pelling, 2010; Birkmann *et al*., 2013). Perceptions and cognitive constructs about risks and adaptation options as well as cultural contexts influence adaptive capacities and thus vulnerability (Grothmann and Patt 2005; Rohmberg 2009; Kuruppu and Liverman 2011; see section 19.4.2.3). SREX stressed that the consideration of multiple dimensions (e.g., social, economic, environmental, institutional, cultural) as well as different causal factors of vulnerability can improve strategies to reduce risks to climate change (see IPCC, 2012, p. 17, 67-106).

Key vulnerability and key risk are defined in Box 19-2. Vulnerabilities that have little influence on overall risk would not be considered key. Similarly, the magnitude or other characteristics of physical impacts, such as glacier melting or sea level rise, are not by themselves adequate to determine key risks, since the consequences of climate change also will be determined by the vulnerability of the exposed society or social-ecological system. Key vulnerabilities and key risks embody a normative component because different societies might rank the various vulnerability and risk factors and actual or potential types of loss and damage differently (see IPCC, 2012, p. 45; IPCC, 2007, p. 785). Generally, vulnerability merits particular attention when the survival of communities, societies, or ecosystems is threatened (see UN/ISDR 2011; Birkmann *et al*., 2011). Climate change will influence both the nature of the climatic hazards societies and ecosystems are exposed to and also contribute to deterioration or improvement of coping and adaptive capacities of systems exposed to these changes. Consequently, many studies

(Wisner *et al*., 2004; Cardona, 2010; Birkmann *et al*., 2011) focus with a priority on the vulnerability of humans and societies as a key feature, rather than solely on the physical impacts of climatic change.

19.2.2.1. Criteria for Identifying Key Vulnerabilities

AR4 WGII Ch. 19 highlighted seven criteria that may be used to identify key vulnerabilities: Here we reorganize and further develop these criteria in order to improve the differentiation between key vulnerabilities, key risks and physical impacts – taking into account recent literature (Blaikie *et al*., 1994; Bohle, 2001; Turner *et al*., 2003a; Turner *et al*., 2003b; Villagrán de León, 2006; Cutter *et al*., 2008; Cutter and Finch, 2008; ICSU - LAC, 2010a; ICSU - LAC, 2010b; UNISDR, 2011; Cardona, 2011; Birkmann, 2011a; IPCC, 2012a; Birkmann *et al*., 2013). The criteria for identifying vulnerabilities as "key" used in the AR4 are: magnitude of impacts, timing of impacts, persistence and reversibility of impacts, likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates, potential for adaptation, distributional aspects of impacts and vulnerabilities, and importance of the system(s) at risk. These criteria do not provide a systematic differentiation of vulnerability and risk. Revised criteria for assessing *key vulnerabilities* used here should provide an improved basis to distinguish between changes in the physical climate and associated physical impacts (like sea level rise), vulnerability and risk for societies or social-ecological systems. The following eight criteria are used to judge whether vulnerabilities are key:

1) *Exposure of a society, community, or social-ecological system to climatic stressors*. While exposure as used is distinct from vulnerability, exposure is an important precondition for considering a specific vulnerability as key. If a system is not at present nor in future exposed to hazardous climatic trends or events, it is less important to consider its vulnerability to such hazards. The exposure to climatic hazards and non-climatic stressors can be assessed based on spatial and temporal dimensions.
2) *Probability that societies or social-ecological systems exposed to climatic changes and associated physical impacts would experience major harm, loss and damages*. Vulnerability is considered key when there is a high probability that a climatic hazard, often in combination with non-climatic stressors (e.g. price fluctuations, migration, land-grabbing), would cause major harm to an exposed and particularly susceptible society or social-ecological system. This criterion can be made specific with vulnerability assessments. For example, communities in low-lying areas in developing countries with limited resources to adapt and a low awareness about climatic hazards are often more vulnerable than regions and communities in highly developed countries that can afford coastal protection systems (Nicholls and Small 2002; Klein *et al*., 2003, p. 109). Criteria that might be used to assess such susceptibilities or sensitivities encompass among other factors poverty and wealth status, demographic characteristics, and aspects of governance (see IPCC, 2012).
3) *Importance of the vulnerable system(s)*. Societies and people in differing regions and cultural contexts view the importance of systems, impacts, and services differently (see Kienberger, 2012). However, the identification of key vulnerabilities is less subjective when it involves those systems that are crucial for the survival of societies or when it refers to resources essential for coping and adapting to adverse consequences, such as important ecosystem services on which societies depend. For example, drought exposed-farmer households in the Sahel are heavily dependent on ecosystem services such as water and fertile soils, and some storm-exposed islands nations are highly dependent on coral reefs. Inability to replace such a system or compensate for potential and actual losses and damages is a feature of importance. Defining key vulnerabilities regarding various societal groups (as in criterion #2), or ecosystem services takes into account the contextual conditions that make these societies or exposed elements or groups highly vulnerable compared to similar systems in other contexts(Leichenko and O'Brien, 2008; O'Brien *et al*., 2009).
4) *Limited ability of societies or communities to cope with the climate-related hazards within existing capacities*. Coping refers primarily to capacities that are available here and now to reduce the negative impacts of climatic stress on communities or social-ecological systems exposed. Coping is part of the formula that determines vulnerability at any one moment in time. Coping also connotes the protection of the current system and institutional settings (see Birkmann, 2011; Birkmann et al. 2013) rather than improving these to increase capacities against climate risks (IPCC 2012, p. 51). Limits of coping provide a criterion for key vulnerabilities.

5) *Limited ability of societies to build adaptive capacities to reduce or limit vulnerability as environmental and climate conditions change*. The capacity of societies (including communities) to build adaptive capacities is a central issue when assessing vulnerability (IPCC 2007, AR4). Adaptation is a continuous process which includes – compared to coping – also learning, experimentation and change of the system exposed (Smithers and Smit, 1997; Pielke Jr, 1998; Smit *et al*., 1999; Frankhauser *et al*., 1999; Adger *et al*., 2005; Smit, 2006; Pelling, 2010). This understanding of adaptation is also based on an emerging consensus from climate change literature (Kelly and Adger, 2000; Yohe, 2002; Pelling *et al*., 2008) where coping describes actions taken within existing constraints (including vision and knowledge), while adaptation signifies expanding the boundaries of those constraints, for instance, through institutional changes (e.g. rule systems, modes of governance) (Pelling *et al*., 2008; Garschagen, 2011; Tschakert and Dietrich; 2012).

6) *Persistence of vulnerable conditions and degree of irreversibility of consequences*. Vulnerabilities are considered key when they are persistent and difficult to alter as well as having a high potential to interact with a hazardous event to produce irreversible negative changes. This is particularly the case when the susceptibility or sensitivity is high, implying that the capacities to cope or adapt are low. In this way, communities or social-ecological systems (e.g. coastal communities dependent on fishing or mountain communities dependent on specific soil conditions) may reach a tipping point that would cause a partial or full collapse of the system, including displacement (see Renaud *et al*., 2010; section 19.4.2.1).

7) *Presence of conditions that make societies highly susceptible or sensitive to cumulative stressors in complex and multiple-interacting systems*. Conditions that make communities or social-ecological systems highly susceptible to additional climatic hazards or that limit their ability to cope and adapt, such as chronic poverty or living in a failed state (e.g. during drought disaster in Somalia) should be taken into account. Also the critical dependence of societies on interdependent, interconnected infrastructure, such as those providing energy/power supply, transport and health care delivery, might lead to complex and multiple-interacting systems with low coping and adaptive capacity (see Chapter 23).

19.2.2.2. Criteria for Identifying Key Risks

Key risks are the product of the interaction of climate-related hazards with key vulnerabilities of exposed societies and communities. A risk would not be considered "key" if the climatic hazard had a low probability and/or magnitude and would affect a society, community or a social-ecological system with low vulnerability.

In contrast to the criteria for identifying key vulnerabilities, the criteria for identifying key risks take into account the magnitude, frequency and severity of hazardous climate trends, events, and physical impacts to which vulnerable systems are exposed. The following four criteria are used to judge whether risks are key:

1) *Magnitude:* Risks are key if associated negative consequences have a large magnitude, determined by a variety of metrics including human mortality and morbidity, economic loss, cultural importance, and distributional consequences (see Schneider *et al*., 2007; Below 2009; IPCC, 2012).

2) *Likelihood that risks will materialize and their timing*. Risks are considered key when there is a high probability that the hazard due to climate change will occur under circumstances where societies or social-ecological systems exposed have very limited capacities to cope or adapt. Risks which materialize in the near term may be evaluated differently than risks which materialize in the distant future, since the time available for building up adaptive capacities is different (Oppenheimer, 2005; Schneider *et al*., 2007).

3) *Irreversibility and persistence of conditions and drivers that determine risks*. Risks are considered key when there is a high probability that they would involve irreversible harm, losses and damages. Persistence of risks refers to the fact that underlying drivers and root causes of these risks cannot be rapidly reduced, or the damage to societal and social-ecological systems cannot be quickly reversed (see point 7 above). Critical infrastructures, such as electric power, communications, and transport networks in developed countries often embody systemic risks due to their interdependencies and the high dependency of vulnerable groups (e.g. elderly) on their services. Moreover, the breakdown of critical infrastructure (e.g. electricity or water supply) can also have long distance impacts (teleconnections) that may result in risks far away from the area where the critical infrastructure is located, and hence it can be more difficult to address these risks in areas potentially affected. In addition, chronic poverty and marginalization, and

insecure land tenure arrangements are drivers of vulnerability that in combination with climatic hazards determine risks which often persist over decades, for example as observed in the Sahel Zone.

4) *Limited ability to reduce the magnitude and frequency or nature of hazardous climatic events and trends and the vulnerability of societies and social-ecological systems exposed*. Risks are considered to be key when societies have very limited means through development (either by reducing emissions of greenhouse gases or improving coping and adaptation) to reduce the magnitude, frequency or intensity of risks due to climatic hazards. These hazards and the vulnerability of societies or social-ecological systems – and hence risk – are also dynamic and change over time, e.g. due to different socio-economic development processes.

19.2.3. Criteria for Identifying Emergent and Emerging Risks

A risk that arises from the interaction of phenomena in a complex system is defined here as an *emergent risk*. For example, unforeseen feedback processes between climatic change, human interventions and processes in natural systems can be classified as emergent risks if they pose a threat to human security. Alternatively, emergent risks could be linked to unprecedented situations, such as the increasing urbanization of low laying coastal areas that are prone to sea-level rise or where new pluvial flooding risk emerges due to urbanization of vulnerable areas not historically populated. An *emerging risk* is a risk that has emerged only recently in the scientific literature in sufficient detail to permit assessment. For example, the initial consequences associated with these risks may have only recently been detected above the natural variability of the climate system, as is the case for certain effects of ocean acidification on calcareous organisms. For clarity, where these emerging risks arise from the interaction of phenomena in a complex system (and are thus also emergent risks) they are discussed in sections 19.3 and 19.4 relating to emergent risks. In this chapter, the only emergent and emerging risks discussed are those which have the potential to become key risks once sufficient understanding accumulates.

19.2.4. Identifying Key and Emergent Risks under Alternative Development Pathways

Key risks are determined by the interaction of physical impacts of climate change with vulnerabilities of societies or ecosystems. Development pathways describing possible trends in demographic, economic, technological, environmental, social and cultural conditions(Hallegatte *et al*., 2011) will affect key risks because they influence both the likelihood and nature of climate changes and physical impacts, and the societal and ecological conditions determining vulnerability. Therefore some risks could be judged to be key under some development pathways but not others. Emergent and emerging risks can depend on development pathways as well, since their identification as potentially key risks may be contingent on future socio-economic conditions.

Different development pathways will lead to different key risks because they affect the magnitude, timing, and heterogeneity of physical impacts of climate change through their effects on emissions and other forcing such as land use change, and consequently on climate change (see Chapter 12, WG1). Components of development pathways such as economic growth, technical change, and policy will influence the rates and spatial distributions of emissions of greenhouse gases and aerosols, and of land use change (Chapter 5, WG3).

Development pathways will also influence the factors involved in identifying key vulnerabilities of human and ecological systems, including both sensitivity to impacts and adaptive capacity(Yohe and Tol, 2002; Füssel and Klein, 2006; Hallegatte *et al*., 2011; O'Neill *et al*., submitted). The size or scale of populations, ecosystems, or economic sectors that are vulnerable to particular impacts will depend on population growth and spatial distribution, economic development patterns, and social systems. The particular elements of the social-ecological system that are most exposed and sensitive to climate hazards, and that are considered most important, will depend on spatial development patterns as well as on cultural preferences, attitudes toward nature/biodiversity, and reliance on climate-sensitive resources or services, among other factors (Adger, 2006; Fuessel, 2009). The degree to which persistent or difficult to reverse vulnerabilities are built into social systems, as well as the degree of inequality in vulnerability across social groups or regions, also depend on elements of development pathways (Adger *et al*., 2009).

19.2.5. Assessing Key Vulnerabilities and Emergent Risks

The criteria above for assessing vulnerability and risk provide a sequence of potential assessment steps. While the first assessment phase would explore whether and how a society or social-ecological system is exposed to climate related hazards, the assessment thereafter would focus on the probability of loss and harm in case an event or events would affect a society or social-ecological system exposed. In addition, the importance of the system at risk and the ability of a society or system to cope and to adapt to these stressors would be assessed. Finally, the application of the criteria would also require the assessment of the irreversibility of the consequences, the persistence of vulnerable conditions as well as the presence of conditions that make societies susceptible. Hence, the assessment criteria focus on the inner conditions of a person, a community (e.g. age structure, poverty), or a social-ecological system as well as on the contextual conditions that influence their vulnerability (e.g. larger governance conditions and systems of norms). Examples of such key vulnerabilities and key risks drawn from other chapters of this assessment are provided in section 19.6 and particularly Table 19-3.

19.3. Emergent Risk: Multiple Interacting Systems and Stresses

19.3.1. Limitations of Previous Approaches Imply Key Risks Overlooked

Interactions between climate change impacts in various sectors and regions, and between these impacts and human adaptation in other sectors and regions, as well as interactions between adaptation and mitigation actions (the latter also considered in section 19.4.3), are generally not included, or not well integrated, into projections of climate change impacts (Warren, 2011). These interactions create emergent risks and/or key vulnerabilities not previously recognized. There is a very large number of potential interactions, and many important ones have not yet been quantified, meaning that some key risks have been overlooked. In some cases, new knowledge about these risks is just now emerging. The six interaction processes listed below, while not exclusive, are systemic and are *likely* to lead to further key vulnerabilities as well as a larger number of less significant impacts. Several of these are discussed in more detail in the following sections.

- Climate change induced biodiversity loss erodes ecosystem services, in turn affecting human systems dependent on those services. (*19.3.2.1)*
- Climate change induced changes in extreme weather events affect human systems and ecosystems, which preconditions these systems and increases vulnerability to the effects of mean climate change. Most impacts projections are based only on changes in mean climate (Rosenzweig and Hillel, 2008).
- Interactions with non-climate stressors: the interaction between climate change impacts and population/economic growth is well studied, but a large literature now addresses interactions of climate change with other factors such as land management, water management, air pollution (which has drivers in common with climate change) and energy production. (*19.3.2.2)*
- Interactions related to climate change and disease emergence. *(19.3.2.3)*
- Co-location of impacts in different sectors creating impact 'hotspots' involving new interactions. (*19.3.2.4)*
- Adaptation designed for one sector interacts with functioning of another sector (e.g. increasing irrigation to crops in response to a drying climate can exacerbate water stress in downstream areas such as wetlands, in cases where the latter provide important water cleaning services). (*19.3.2.5)*

19.3.2. Emergent Risks

19.3.2.1. Emergent Risks Arising from the Effects of Degradation of Ecosystem Services by Climate Change

Biodiversity loss is linked to disruption of ecosystem structure, function and services (Díaz *et al*., 2006; Gaston and Fuller, 2008; Maestre *et al*., 2012; Midgley, 2012). A large number of studies project how species ranges are projected to decline in size as mean climate changes (see Chapter 4), e.g. a study of 50,000 species found that 57±6% of widespread & common plants and 34±7% of widespread & common animals are projected to lose ≥50% of their current climatic range by the 2080s (Warren *et al*., in press) and there is *high confidence* that

projected climate changes imply increased extinction risk for a substantial fraction of species during the 21st century (see Chapter 4). These processes of decline in species richness and extinction will combine with damage due to climate-change induced increases in short-term extreme weather events expected for some regions, as well as (see WGI SPM and 7.6.2) increased forest losses due to fire. The resulting potential for disruption of the functionality of the ecosystems translates into an emergent risk of large-scale loss of ecosystem services in both terrestrial and marine systems (Mooney *et al*., 2009; Table 19-3, Entry 2, Chapter 19). At-risk services include water purification provided by wetlands, air purification by forests, crop pollination by insects, coastal protection from storm surge by mangroves and coral reefs, regulation of pests and disease, recycling of waste nutrients, and removal of carbon from the atmosphere (Chivian and Bernstein, 2008, Chapter 4). Biodiversity loss has now also been linked to increased transmission of infectious diseases such as Lyme, Schistosoma and hantavirus in humans, and West Nile virus in birds, creating a newly emerging dimension to the emergent risks resulting from biodiversity loss (Keesing *et al*., 2010).

The following studies provide examples of projected ecosystem service loss in the agricultural sector due to climate change: projected crop damage due to increased prevalence of pest species including *Fusarium graminearum* (a fungal disease of wheat), the European corn borer, the Colorado beetle, bakanae disease and leaf blights of rice, and the Western corn root worm (Petzoldt and Seaman, 2006; Kocmankova *et al*., 2010; Huang *et al*., 2010; Chakraborty and Newton, 2011; Magan *et al*., 2011; Aragón and Lobo, 2012); and projected declines in crop yields due to climate change effects on pollinating species (Rosenzweig and Hillel, 2008; Kuhlmann *et al*., 2012; Giannini *et al*., 2012; Abrol, 2012; Bedford *et al*., 2012). These effects are simultaneous with climate change's direct effects on yields through changing temperature, precipitation, and ambient carbon dioxide concentrations, creating an emergent risk. Climate change has caused, or is projected to cause range expansion in a number of weeds that have the potential to become invasive (Bradley *et al*., 2010a; Clements and Ditommaso, 2011). Invasive species can damage agriculture and cause extinction of other species, with attempts to control them being extremely costly (eg $120 billion annually in the USA, Crowl *et al*., 2008). Whilst the balance of gains and losses for invasive species will vary locally (Bradley *et al*., 2010b) and no single aspect stands out, any one of the mechanisms mentioned in this paragraph has the potential to cause outcomes that are very damaging and act in synergy with existing climate change impacts on agriculture. Hence, these various susceptibilities to loss of ecosystem services taken together comprise a key vulnerability, and in interaction with climate change, an emergent risk.

The global value share of pollination of crops for 2005 has been calculated as 153 billion Euro (Table 4.6). Similarly, the value of the ecosystem services of pollinators for crops and wild plants combined in the UK has been estimated at UK £430 million per year, yet this service is currently becoming less effective (NEA, 2011). Climate change impacts on pollinators therefore places these valuable services at risk, and disruption of wild plant pollination will also affects animals which are dependent upon those plants (see Chapter 4). An increase in woodland cover from 6 to 12% of the UK's land area over the past 60 years (with the reverse being a measure of the cost of degradation) was valued at £680 million per year in carbon sequestration value alone (NEA, 2011). Ecological function analysis for Chinese terrestrial ecosystems yielded estimated economic values of approximately 0.3-1.6 x 10^{13} Yuan annually for services such as CO_2 fixation, O_2 release, nutrient recycling, soil protection, water holding capacity and environmental purification (Ouyang *et al*., 2006). Similarly, the value of ecosystem services in US forests has been estimated at values ranging from US$1 to 6 billion annually for climate regulation, US$4-54 billion for biodiversity, and US$1 to 100 billion annually for recreation (Krieger, 2001). The potential loss of coral reefs (section 19.3.2.4) would result in a loss of income of $Au4 billion to the Australian economy from international tourism, of US$1.6 billion to the Caribbean economies for tourism and fishing on reefs, and loss almost equal to the value of the entire economy of the Maldives and the Seychelles (Hoegh-Guldberg *et al*., 2011). Such costs are represented only very crudely, if at all, in aggregate global models of the economic impacts of climate change where 'non-market impacts' are estimated very broadly if at all (section 19.6.3.5). These large costs show how human systems are vulnerable to loss of ecosystem services, and hence this comprises a key risk as defined in 19.2.

Some of the work on degraded ecosystems and their interaction with economic sectors examines the cost of restoring ecosystem services. For example, interviewed households along the Platte River (US) showed a willingness to pay, in terms of increased water bills, an additional US$20 per month in order to improve five ecosystem services (i.e. natural purification of water, erosion control, habitat for fish and wildlife, dilution of

wastewater, and recreation use) (Loomis *et al.*, 2000), which would provide US$19 to US$70 million dollars which greatly exceeds the estimated costs of improving degraded ecosystem services (US$1.13 to US$12.3 million). A meta-analysis of 89 studies looking at the restoration of ecosystem services measured using 526 different metrics found that restoration increased the amount of biodiversity and ecosystem services by 44 and 25% respectively, but the restored services were still lower than those in intact ecosystems (Benayas *et al.*, 2009). Hence, although restoration of damaged ecosystems may often be cost-effective, it can only partially compensate for loss of services.

Concomitant stress from land use change adds to the extinction risk from climate change, increasing the projected extinction rate (e.g. Sekercioglu *et al.*, 2012) and hence an emergent risk of ecosystem service loss. Empirical studies reveal that ecosystem impacts due to habitat loss correlate with current maximum temperature and recent precipitation decline, indicating a synergy between climate change and habitat loss effects (Mantyka-Pringle *et al.*, 2012). Due to land use change, adaptation to climate change is now impeded by the fragmented nature of natural habitats.

Land clearing also releases carbon to the atmosphere and removes carbon sinks (WGI section 6.4.3.3) such as old growth forests which would otherwise continue to accumulate carbon (Luyssaert *et al.*, 2008) in the future. A new approach has quantified the 'Greenhouse Gas Value' of ecosystems (Anderson-Teixeira and DeLucia, 2011), taking into account both fluxes and storage of carbon, implying that published values of ecosystem services from carbon sequestration have tended to underestimate their importance due to a tendency to consider only the carbon currently stored in the systems.

19.3.2.2. Emergent Risk Involving Non-Climate Stressors: the Management of Water, Land, and Energy

One of the most important interactions affecting the well-being of humans and ecosystems and the level and rate of climate change, are those involving human management of water, land, and energy. These profoundly affect the amount of carbon which can be stored in terrestrial ecosystems, the amount of water available for use by humans and ecosystems, and the viability of adaptation plans for cities or protected areas, for example. Failure to manage land, water and energy in a synergistic fashion can exacerbate climate change impacts globally (Wise et al 2008, Searchinger *et al.*, 2008; Lotze-Campen *et al.*; 2009; Warren *et al.*, 2011).

Projected changes in climate variability combined with water extraction leads to an emergent risk: that of water stress exacerbated by the removal of groundwater which serves as 'an historical buffer against climate variability' (Green *et al.*, 2011). The use of energy by the water sector, including domestic use for heating, accounts for between 5-6% of the greenhouse gas emissions of the US and India(Green *et al.*, 2011; Rothausen and Conway, 2011). Extraction and conveyance of water for irrigation is energy intensive and this demand is projected to rise as adaptation to climate change and increasing food demand drives the need for an expansion of irrigated cropland. In areas where drought is frequent, water might be provided through construction and use of de-salinisation plant. All this has implications for projected energy use and hence mitigation strategies. However, there are opportunities for adapting the agricultural sector to climate change in drying regions in ways which reduce greenhouse gas emissions, such as advanced irrigation systems(Rothausen and Conway, 2011).

The second issue is that of groundwater extraction, which is *likely* to increase as an adaptation to climate change, since current demand for surface water will not be met under various scenarios of a changed climate(Barnett *et al.*, 2008). For example, following a ten-fold increase in groundwater extraction in China, 70% of the irrigated cropland in China is now groundwater fed, and it is estimated that 0.5% of the country's greenhouse gas emissions are attributable to exploitation of this resource(Wang *et al.*, 2012). The effects of climate change on groundwater are varied with some areas expecting decreased recharge, whilst others are projected to experience increased recharge (Green *et al.*, 2011). However, in areas where extraction rates increase or recharge decreases, water tables will be depleted with consequence for ecosystems and the human systems (such as agriculture, tourism and recreation) which depend upon them, while water quality will also decrease. One projection shows insufficient water availability in Africa, Latin America and the Caribbean to satisfy both agricultural demands and environmental regulations by 2050, owing to increases in demand for water use for municipal and industrial use, combined with increases in demand for food, a situation that is exacerbated by climate change (Strzepek and Boehlert, 2010).

Concurrently, the use of water by the energy sector, by thermo-electric power generation, hydropower and geothermal energy, or biofuel production, can also be an issue (Pittock, 2011) especially in cases where energy generation is concentrated in arid regions, whilst Kelic (2009) have explored how the energy sector could best adapt to drought conditions. Other studies have addressed the energy, water, land nexus that drought conditions present to the agricultural and energy sectors (Tidwell *et al*., 2011; Skaggs *et al*., 2012).

Simulations of stringent mitigation (e.g. that required to constrain radiative forcing to 2.6 W/m^2 during the 21st century) show an economic necessity to include a major contribution from biofuels (van Vuuren *et al*., 2011). If production is not carefully managed, biofuel feedstocks can displace land for food cropping or natural, unmanaged ecosystems. Reductions of greenhouse gas emissions from biofuel production and use (compared to fossil fuels) may be offset partly or entirely for decades or centuries by emissions from the resulting indirect land-use changes (iLUC) (IPCC SRREN, 2011, Chapter 2; Bringezu *et al*., 2009; Van Vuuren *et al*., 2010a), some of which are not only indirect but have transboundary and/or distant impacts (see 19.4). The placement of a carbon tax (as a surrogate for the effect of a variety of policies) to fossil carbon only, with a goal of limiting CO_2 concentrations to 450 ppm-550 ppm, is projected to lead to large scale deforestation of all natural forests by the end of the 21st century, with conversion of most other natural ecosystems, in part due to enhanced biofuel production (Wise *et al*., 2009; Mellilo *et al*., 2009a,b). This could bring so much terrestrial carbon, converted into CO_2, in the atmosphere that it could offset partly or entirely the effect of substituting fossil fuel with biocarbon and obstruct the original goal of limiting atmospheric CO_2. If instead the tax is applied also on terrestrial carbon, the deforestation could slow down or even reverse, depending on the level of the tax. Alternatively (or additionally), land set-asides such as the Conservation Reserve Program in the US may be more effective at long-term GHG mitigation than maize-ethanol (Piñeiro *et al*., 2009).

Indirect land use changes can be reduced using the strategies for reducing food-system competition through markets, as discussed in section 19.4.1. Liquid biofuels can mitigate GHG emissions when used in place of fossil fuels such as gasoline, diesel, and more carbon-intensive fuels from tar sands and heavy oil (Cherubini *et al*., 2009). Successful mitigation, however, is highly dependent on what feedstock is used, how it is grown, and how well subsidies and incentives prioritize GHG reductions. Second-generation biofuels, those based on non-food crops (grasses, algae, timber) and agricultural residues, are expected to offer reduced emissions of GHG and other air pollutants compared to most first-generation biofuels due primarily to less adverse interactions with food-systems (Plevin, 2009; Fargione, 2010; Sander, 2010; Cherubini, 2010). Further, bioelectricity and biogas may both be more successful at mitigating GHG emissions than liquid biofuels (Power and Murphy, 2009; Campbell *et al*., 2009).

However, there are many equally compelling reasons for a country to encourage biofuel production including, among other things, competition for high oil prices, rural development and reduced oil imports – all of which could be prioritized over GHG reductions depending on the country (Cherubini *et al*., 2009). Another inherent conflict is that per-litre GHG emissions *decrease* as agriculture is further intensified through row cropping, fertilizer and pesticide use, and irrigation, while other per-litre environmental impacts *increase* (Burney *et al*., 2010; Grassini and Cassman, 2012). Conflicting biofuel deployment policies and priorities, and interactions with food-systems could therefore lead to a number of emergent risks as liquid biofuel supply increases, as shown in the Table 19-1.

[INSERT TABLE 19-1 HERE
Table 19-1: Emergent risks related to biofuel production as a mitigation strategy.]

19.3.2.3. Emergent Risks Involving Health Effects and Disease Emergence

Climate change will act through numerous direct and indirect pathways to alter the prevalence and distribution of diseases that are climate and weather sensitive. These effects will differ substantially depending on current epidemiologic profiles, reflecting the level of development and access to clean and plentiful water, food and access to adequate sanitation and health care resources. Furthermore, the impact of climate change will differ within and between regions, depending upon the adaptive capacity of critical public health infrastructure that ensures access to clean food and water.

A principal emergent global risk is malnutrition secondary to ecological changes and disruptions in food production as a result of changing rainfall patterns, increases in extreme temperatures and precipitation events (IPCC, 2012), and increased atmospheric CO_2 (Taub *et al.*, 2008; Lobell and Burke, 2010). Modeling of the magnitude of the effect of climate change on future under-nutrition in five regions in South Asia and sub-Saharan Africa in 2050 (using the SRES A2 emissions scenario) suggests an increase in moderate nutritional stunting, an indicator linked to increased risk of death and poor health (Black *et al.*, 2008), of 1% to 29% compared to a future without climate change, and a much greater impact on severe stunting of 23% for central sub-Saharan Africa and 62% for south Asia (Lloyd *et al.*, 2011). The impact of climate induced drought and precipitation changes in Mali include the southward movement of drought-prone areas which would result in a loss of critical agriculturally-productive land by 2025 and increase food insecurity (Jankowska *et al.*, 2011).

In developed countries and large, highly populated megacities with developed public health infrastructure, principal emergent risks include increased injuries and fatalities as a result of severe storms and heat waves (see 19.6.3.3); changes in vector biology and disease ecology that impact infectious diseases; water and food contamination; increased pollen production leading to increases in allergic airway diseases (see 19.5.3); and respiratory and cardiovascular morbidity and mortality secondary to degraded air quality and ozone formation (see 19.6.3.3).

Increase in heat-related morbidity and mortality subsequent to the increase in the severity, duration, and frequency of heat waves (Luber and McGeehin, 2008) in urban areas is an emergent risk. These impacts will be greatest in urban areas with a pronounced urban heat island effect (Kovats and Hajat, 2008). The coupling of the increasing vulnerability of an aging population and a global shift to urbanization will increase the risk of relatively higher mortality from exposure to excessive heat (Knowlton *et al.*, 2007).

While the association between ambient air quality and health is well established, there is an increasingly robust body of evidence linking spikes in respiratory diseases to weather events and to climate change, so that this interaction is an emergent risk. In New York City, for example, each single degree (Celsius) increase in surface temperature has been associated with a 3% increase in same-day hospitalizations due to respiratory diseases, and an increase of up to 3.6% in hospitalizations due to cardiovascular diseases (Lin *et al.*, 2009). The principal pathways through which such respiratory health outcomes will be exacerbated by climate change are through increased production and exposure to tropospheric (ground-level) ozone, smoke produced by wildfires, and increased production of pollen (D'Amato *et al.*, 2010). Many of the same populations that are vulnerable to health effects from heat waves show increased risk for effects from poor air quality induced by heat, including: the very young and the very old and those with preexisting medical conditions, including respiratory and cardiovascular disease (see 19.6.3.3).

Projected changes in precipitation, temperature, humidity, and water salinity, have potential to affect the distribution and prevalence of food- and water-borne diseases resulting from bacteria and other pathogens, and increases in the frequency and range of harmful algal blooms (Curriero *et al.*, 2001; Moore *et al.*, 2008). Climate change and increased climatic variability would affect incidence of vector-borne diseases such as plague, Lyme's disease, malaria, hantavirus, and dengue fever which exhibit distinct seasonal patterns and sensitivity to ecologic changes (Githeko *et al.*, 2000; Gage, 2008; Parham *et al.*, 2011 submitted). These changes to food, water, and vector-borne diseases represent additional emergent risks.

19.3.2.4. Spatial Convergence of Multiple Impacts: Multi-Impacts Hotspots

"Hotspot" is an equivocal term that is defined and used in various manners (see also Box 21-4 in Chapter 21 for detail). In this chapter, we define a *multi-impacts hotspot* as a region where climate-change induced impacts in one sector affect other sectors in the same region or a region where climate change impacts in different sectors are compounded, resulting in extreme or high-risk consequences. The frequent and ongoing spatial and temporal coincidence of impacts in different sectors in the same region could have consequences that are more serious than simple summation of the sectoral impacts would suggest. Such synergistic processes are difficult to identify through sectoral assessment and apt to be overlooked in spite of their potential importance in considering key vulnerabilities. For example, a large flood in a rural area may damage crop fields severely, causing food shortages(Stover and

Vinck, 2008). The flood may simultaneously cause a deterioration of hygiene in the region and the spread of water borne diseases (Schnitzler, 2007; Hashizume *et al*., 2008; Kovats and Akhtar, 2008). The coincidence of disease and malnutrition can thus create a multi-impacts hotspot for health impacts, with the elderly and children most at risk.

As a systematic approach, identification of multi-impacts hotspots could be achieved by overlaying spatial data on impacts in multiple sectors, but this cannot indicate synergistic influences and dynamic changes in these influences quantitatively. For global analysis, certain types of integrated assessment models which allow spatial analysis of climate change impacts have been used to identify regions that are affected disproportionately by climate change (Fussel, 2010; Tol and Fankhauser, 2008, Kainuma et al., 2003; Bowman et al., 2006; Warren et al., 2008). Recent efforts attempt to collect and archive spatial data on impact projections and facilitate their public use. These have created overlays for identifying hotspots with web-GIS technology (Adaptation Atlas (Vajjhala, 2009)). The Union of Concerned Scientists (2011) also identified many locations which could be classified as a multi-impacts hotspot based on robust scientific evidences published in peer-reviewed literature (Union of Concerned Scientists, 2011). There are also efforts to coordinate impacts assessments based on shared future scenarios at various spatial scales(Parry *et al*., 2004; ISI-MIP, 2012).

[INSERT FIGURE 19-2 HERE
Figure 19-2: Some salient examples of multi-impacts hotspots identified in this assessment.]

To illustrate some different types of multi-impacts hotspots where climate change impacts coincide and interact, the following examples are provided.

1) The Arctic is an example of a regional multi-impact hotspot, where the culture of indigeneous people (Crowley, 2011) is projected to be exposed to the disruption, and possible destruction of, their hunting and food sharing culture (see Chapter 28). This hotspot is due to the combination of sea ice loss and the concomitant potential extinction of the animals dependent upon the ice (Johannessen and Miles, 2011). Thawing ground is also disrupting transportation, buildings and infrastructure whilst there is increased exposure to storms. Arctic ecosystems are also at risk (Kittel *et al*., 2011).
2) Coral reefs are highly threatened due to the synergistic effects of sea surface temperature rise and perturbed ocean chemistry, which reduces calcification and also increases sensitivity to other impacts such as the loss of coral symbionts (Chapter 6). The importance of a hotspot of reef sensitivity to climate change in the area of greatest reef diversity in the world was recently highlighted in the near-equatorial Indo Pacific(Lough, 2012). A second hotspot for warming and thus damage to reefs was identified around Micronesia, Mariana Island and Papua New Guinea (Meissner *et al*., 2012).
3) Cities in deltas are often impact hotspots, being subject to sea level rise, storm surge, coastal erosion, saline intrusion and flooding. Extreme weather events can also disrupt access to food supplies, causing a malnutrition risk. Ericson *et al*. (2006); Chapter 24 revealed that over 6 million people would be at risk of enhanced inundation and increased coastal erosion in three megadeltas and 8.7 million in 40 deltas, absent measures to adapt. Examples of delta areas at risk include Mumbai, Dhaka and the Mekong (see Chapter 8, Chapter 24, and section 19.6.3.4).

General equilibrium economic models (see Chapter 10) may facilitate quantitative evaluation of synergistic influences. An analysis of the EU by the PESETA project evaluated sub-regional welfare loss by considering impacts on agriculture, coastal system, river floods, and tourism together in the CGE (Computable General Equilibrium) model, which is designed to represent interrelationships among economic activities of sectors, and indicated the largest percentage loss in Southern Europe (Ciscar *et al*., 2011)It should be noted, at any scale, choices of sectors are strongly constrained by availability of data or evaluation methods and they are not comprehensive.

19.3.2.5. Maladaptation

Maladaptation refers to adaptation strategies that increase a population's or sector's vulnerability to climate change. It can be viewed as a type of emergent risk since it arises from an interaction of a response by one group of people to climate change impacts which then interacts negatively with another group, often in a different sector or region. Maladaptation is discussed in detail in Chapter 14.7

19.4. Emergent Risk: Indirect, Trans-Boundary, and Long-Distance Impacts

Climate change impacts can have consequences beyond the regions in which they occur. Such long distance interactions may be mediated by global trade systems – the most prominent example of this is the global food trade system. However, the danger with relying only on global trade to mediate impacts is that competitive market forces do not account for considerations of justice. As prices on food, land, and other resources increase, those most in need may end up being the least able to pay (see section 19.6.1.2 on differential vulnerability). Additionally, both mitigation and other adaptation responses that are implemented on the ground can have unintended consequences beyond the locations in which they are implemented. All of these mechanisms can create emergent risks.

19.4.1. Indirect, Trans-Boundary, and Long-Distance Impacts of Climate Change Impacts on Agricultural Yields: Food Trade Patterns, Prices, Malnutrition

Climate change impacts on agriculture can have consequences beyond the regions in which those impacts are directly felt, through the global food trade system. Food access can be inhibited by rising food prices, as demonstrated during recent price rise episodes that resulted from the combination of poor weather in certain world regions combined with a demand for biofuel feedstocks, increased demand for grain-fed beef in China, and historically low levels of food stocks (Abbot and deBattisti, 2011; Adam and Ajakaiye, 2012). These episodes provide an analog elucidating how reduced crop yields due to climate variability impacts and biofuel cropping create a risk of malnutrition: hence this interaction of climate change with the food system via markets comprises an emergent risk of the impacts of climate change acting a distance. For further information see 7.2.2. on food security and 7.3.2.1.1. on how climate change can impact crop yields.

One study found that climate change may have already offset 30-years worth of technology-related increases in crop yields in Russia, Turkey, Mexico (wheat) and China (maize) (Lobell *et al*., 2011). Another study identified areas where past climate variability has induced sudden or prolonged drops in food production, e.g., Ukraine (a 13% decline in a single year due to high summer temperatures) and the Sahel (decadal scale losses due to prolonged drought and high temperatures; Battisti and Naylor, 2009). In the next few decades, areas where crop yields are projected to decline such as sub-Saharan Africa and the Sahel may come to rely more strongly on imported food (Schmidhuber and Tubiello, 2007). Whilst some studies (Jaggard *et al*., 2010) conclude that in the next few decades there may be increases in crop yields in temperate regions which may compensate in global terms for the losses in tropical regions (FAO, 2008), a recent empirical study suggests that these benefits may not be realized, based on indications that, to date, the positive effects of CO_2 fertilisation on yields and the effects of changes in precipitation and temperature have offset one another (Lobell and Field, 2007). Battisti and Naylor (2009) used climate projections from IPCC AR4 to show that by the end of the century, there is a probability of over 90% that growing season temperatures in the tropics and subtropics will exceed even the most extreme seasonal temperatures recorded from 1900 to 2006. Compared to the assessment in AR4, the evidence points to an *increased* risk that tropical and sub-tropical regions will experience significant crop yield declines due to climate change (see 7.3.2.1.1.). Taken together, regional climate change impacts on crop yields would result in increased prices of food commodities on the global market (Battisti and Naylor 2009; Lobell *et al*., 2011) even under an assumption of barrier-free ability to change the areas under cultivation (Juliá and Duchin, 2007).

Weather-induced yield losses which have affected food prices in many countries have already been documented in Australia and Europe in recent years (FAO, 2008; World Bank, 2011) – for example increasing the number of malnourished people by 75 million in 2007 (FAO, 2008). Climate change is projected to increase the frequency of extreme weather that can reduce crop yields and increase their year-to-year variability (Diffenbaugh *et al*., 2012; Urban *et al*., 2012), and there is some specific evidence that climate change induced yield losses are already affecting food prices (Lobell *et al*., 2011). Furthermore, developing countries that have limited financial capacity for trade, and/or food distribution networks may be damaged by increases in extreme weather events (FAO, 2008) leading to increased risk of poverty and malnutrition. One study used historical vulnerability to extreme weather events to project that Bangladesh, Mexico, Mozambique, Malawi, Tanzania and Zambia would be most at risk from

future extreme weather events under 21st century climate change in the SRES A2 scenario (Ahmed *et al*., 2009). Developed countries which currently enjoy imported foods from tropical regions that become affected by climate change, would see the prices of those commodities rise. More generally, pressure on land use for biofuels is *likely* to further exacerbate food prices (see section 19.3.2.2).

On longer timescales, new techniques for assessing climate change impacts on yields of soybean, maize and cotton in the United States (Schlenker and Roberts, 2009) result in higher projections of yield declines compared to studies assessed in AR4: yield losses reach 30-46% by the end of the century under a low emissions scenario, or 63-82% under a high emissions scenario. However, these approaches are not necessarily accepted as better than earlier studies (see section 7.3.2.1.1.). Global rice prices may be particularly sensitive to climate change (Chen et al 2012), potentially rising by 7-13% in the wake of projected 1.6-2.7% losses in yield resulting from a combination of climate change and sea level rise. Another study (Warren *et al*., 2011) highlights that 50% of the global area where crops could be grown is projected to become less suitable for cultivation by the end of the century if global temperatures reach 4°C. Arnell *et al*. (2013) explains that once regional temperatures exceed 1° to 3°C above 1961-1990 mean, crop suitability falls back. A recent report (Foresight, 2011a) highlights the combined agricultural land losses expected in the next 40 years, due to desertification, erosion and sea level rise (the latter leading to increased salination). The report does not estimate the percentage of agricultural land involved, but if large, such changes would further increase global food prices, increasing the risk of poverty and malnutrition (World Bank, 2011).

Producing a significant proportion of energy from biofuels without inducing pressure on food and ecosystems through indirect land use change would require increasing available agricultural supplies through either decreasing existing demand and/or increasing production through intensification/extensification. Hence, there can be important interactions between global emissions mitigation policies and land management that can either confound, or contribute to, mitigation (Van Vuuren *et al*., 2011). Markets will respond to increasing liquid biofuel production in one of two ways: either through reduction in other demands for the feedstock crop or an increase in the supply, both of which will happen as commodity prices start to rise. Accurately tracking and quantifying the direct and indirect impacts of biofuel production on the food-system has become an intense area of study since AR4. As witnessed in the United States, US maize-ethanol production increased 800% since 2000, with maize commodity prices more than tripling and harvested land growing by more than 10% (mainly at the expense of soy (USDA, 2011). Ethanol recently consumed one quarter of US maize production, even after accounting for feed by-products returned to the market (USDA, 2013). However, isolating biofuels' exact contribution to food-system changes from other factors such as extreme weather events, climate change, changing diets, and increasing population have proven difficult (Zilberman, 2011). Still, estimates of the supply and demand elasticity of basic grain commodities (Roberts and Schlenker 2009) lead to a prediction that the 2009 US Renewable Fuel standard could increase commodity prices of maize, wheat, rice, and soybeans by roughly 20%, assuming one third of the calories used in ethanol production can be recycled as animal feed (Roberts and Schlenker, 2010).

Market responses to increased commodity prices are often the same mechanisms being viewed to potentially increase supply to the point where biofuels and food production can co-exist. These strategies can be grouped as follows: increasing supply either through extensification or intensification, and decreasing demand either by lifting biofuel mandates or reducing commodity usage from other demands.

The central question with regards to increasing the supply of commodity crops is how much will come from the intensive margin (higher yields per acre), and how much will come from the extensive margin (more acres). Keeney and Hertel (2009) argue that yields respond to prices and Foley *et al*. (2011) project that closing global 'yield gaps' for 16 important food and feed crops on lower productivity lands could increase agricultural supply by 58%. On the other hand, Roberts and Schlenker (2010) find that, historically, growing area responds to exogenous price shocks. If additional supply comes in part from planting new acres, Fargonie *et al*. (2008) and Searchinger *et al*. (2008) find large CO_2 effects of indirect land use change (iLUC) – currently one of the largest concerns surrounding liquid biofuels, both due to the magnitude of its potential impact and the uncertainty in accurately quantifying it. Deforestation would result in large indirect CO_2 emissions, as does the production of biodiesel using palm oil on peatlands that are drained (Miettinen *et al*., 2012). A study of biofuel production in Brazil (Barr *et al*., 2011) finds that once pasture is incorporated in the analysis, expansion into unexploited land is minor, i.e., most of additional cropland is predicted to come from conversion of pastureland. However, loss of pasture to biofuel might also trigger

iLUC if the density of livestock operations is not increased in tandem. To the extent that biofuel feedstock crops are grown on areas that were previously fallow or degraded, the iLUC effects might be minimized and CO_2 potentially sequestered (IPCC SRREN 2012; Fargione *et al*., 2010) – although the amount, alternative uses, and potential productivity of so-called degraded lands are still contested (Dauber *et al*., 2012).

Market forces will impact demand for feedstock crops as prices increase. These reactions mirror many of the deliberate strategies to influence demand in the hopes of freeing up supply for biofuel production and/or minimize its iLUC impacts. Dietary changes could reduce the land requirements of food cropping embodied in these tradeoffs. A transition to a globally-implemented vegetarian diet would free up 2700 Mha of pasture and 100 Mha of cropland – a combined area representing approximately 70% of current agricultural and pasture land – much of which could then be used for biofuel cropping (Stehfest *et al*., 2009), whilst the remainder could revert to natural vegetation becoming a carbon sink (see 19.3.2.1). Another study found that eliminating meat from human diets could increase available calories by 49% (Foley *et al*., 2011). While extreme and an improbable response, these studies demonstrate that even small changes to diets and meat consumption could have large impacts. Reducing food-system losses might be another way demand responds to increased commodity prices. A recent FAO study found that approximately one third of food is never consumed – with losses in developed countries coming more from the consumer end (post-purchase spoilage before use) and losses in developing countries coming more from the production end (farm losses, spoilage before reaching markets) (Gustavsson *et al*., 2011). On the other hand, given that demand for biofuels is supported by mandates and subsidies, there has been a growing call for lawmakers to lift mandates or implement moratoriums on liquid biofuel development until the direct and indirect impacts on the food system, the climate and food security are better understood. A move to second-generation liquid biofuels or other forms of bioenergy such as bioelectricity or biogas, those that utilize non-food, crop residue or forest-based biomass, might help alleviate concerns. However, depending on where and how new feedstocks are grown they too could introduce their own iLUC impacts (Zilberman *et al*., 2011) and/or N_20 agricultural emissions uncertainty (Meyer-Aurich, 2012).

19.4.2. Indirect, Trans-boundary, and Long-Distance Impacts of Adaptation

Risk can also emerge from unintended consequences of adaptation (see 19.3.2.5), and this can act across distance, if for example, there is migration of peoples or species from one region to another. Adaptation responses in human systems can include land use change, which can have both trans-boundary and long distance effects; and changes in water management, which often has downstream consequences. In some cases such interactions may contribute to conflict.

19.4.2.1. Human Migration and Displacement

Human migration is one of many possible adaptive strategies or responses to climate change (Reuveny, 2007; Piguet 2010; Tacoli, 2009; McLeman, 2011), assessed in detail in Chapter 12 in the context of the many other causes of migration. Displacement refers to situations where choices are limited and movement is more or less compelled by land loss due to sea level rise or extreme drought, for example (see AR5 WGII chapter12.4). A number of studies have linked past climate variability to both local and long distance migration (see review by Lilleør and Van den Broeck, 2011). In addition to positive and negative outcomes for the migrants, migration from one region results in significant indirect, (and in some cases, long distance) effects on people and states in other regions. Consequences for receiving regions, determined by a variety of metrics, could be both positive and negative, as may also be the case for sending regions (McLeman, 2011; Foresight, 2011b; AR5 WGII Chapter 12). An emerging literature examines potential changes in migration patterns due to future climate changes, but projections of specific positive or negative outcomes are not yet available. Furthermore, recent literature underscores risks previously ignored: risk arising from the lack of mobility in face of a changing climate, and risks entailed by those migrating into areas of direct climate-related risk, like low-lying coastal deltas (Foresight, 2011b; see Chapter 12).

Climate change induced sea level rise, in conjunction with storm surges and flooding, creates a threat of temporary and eventually permanent displacement from low-lying coastal areas, the later particularly the case for small island states (Pelling and Uitto 2001; Chapter 12). The extent to which these responses are employed will depend on

whether governments develop strategies such as relocating people from highly vulnerable to less vulnerable areas nearby and conserving ecosystem services which provide storm surge protection (Perch-Nielsen 2004) in addition to so-called "hardening" such as building sea walls and storm barriers (Nordenson and Seavitt 2011). Numbers of people at risk from coastal land loss have been estimated (Nicholls and Tol, 2006; Ericson *et al*., 2006; Nicholls *et al*., 2011) but projections of resulting anticipatory migration or episodic and permanent displacement are not available.

Taken together, these studies indicate that climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). Urbanization is a pervasive aspect of recent migration which brings benefits but, in the climate change context, also significant risks (see 19.2.3, 19.4.1, 19.6.1, 19.6.2; 19.6.3.3; Chapter 8). While a literature projecting climate-driven migration has emerged (Chapter 12.4), there is as of yet insufficient literature to permit assessment of projected region-specific consequences of such migration. Nevertheless, the potential for negative outcomes from migration in such complex, interactive situations is an emergent risk of climate change, with the potential to become a key risk (Table 19-3, Entry 1, Chapter 19).

19.4.2.2. Conflict and Insecurity

Violent conflict between individuals or groups arises for a variety of reasons (section 12.5). A large number of quantitative empirical studies have implicated climatic events as a contributing factor to the onset or intensification of personal violence, group conflict and social instability in contexts around the world and at temporal scales ranging from a climatologically anomalous hour to an anomalous millennium (Hsiang and Burke, 2012). Because most empirical studies have been released after AR4 (Kenrick and Macfarlane, 1986; Vrij *et al*., 1994; Cohn and Rotton, 1997; Anderson *et al*., 2000; Cullen *et al*., 2000; Rotton and Cohn 2000; DeMenocal, 2001; Haug *et al*., 2003; Miguel *et al*., 2004; Levy *et al*., 2005; Miguel, 2005; Mehlum *et al*., 2006; Kuper and Kropelin, 2006; Zhang *et al*., 2006; Hendrix and Glaser, 2007; Jacob *et al*., 2007; Zhang *et al*., 2007; Grove, 2007; Yancheva *et al*., 2007; Burke *et al*., 2009; Bai and Kung, 2010; Burke and Leigh, 2010; Tol and Wagner, 2010; Hidalgo *et al*. 2010; Buckley *et al*., 2010; Bohlken and Sergenti, 2010; Patterson *et al*., 2010; Hsiang *et al*., 2011; Harari and Ferrara, 2011; Chaney, 2011; Bruckner and Ciccone, 2011; Zhang *et al*., 2011; Burke, 2011; Larrick *et al*., 2011; Buntgen *et al*., 2011; Sarsons, 2011; Couttenier and Soubeyran, 2011; Hendrix and Salehyan, 2012; Theisen, 2012; O'Laughlin *et al*., 2012; Kennett *et al*., 2012; Fjelde and von Uexkull, 2012; Dell *et al*., 2012; Ranson, 2012) the possibility that climate change will alter patterns of violence is an emerging risk. The result that high temperature exacerbates modern violence is the most consistent empirical finding, having been reported at spatial scales ranging from the individual level (Vrij *et al*., 1994; Ranson, 2012) to the communal level (O'Laughlin *et al*., 2012; Fjelde and von Uexkull, 2012) to the national level (Burke *et al*., 2009; Dell et al, 2012) to the global level (Hsiang *et al*., 2011).

It remains unknown whether climatic events contribute to the likelihood of violence through one or many of the pathways discussed in section 12.5 (Hsiang and Burke, 2012; Scheffran *et al*., 2012; Bernauer *et al*., 2012), and some authors have indicated that the identification of specific mechanisms is important for attribution and projections of future rates of violence (Sutton *et al*., 2010; Buhaug, 2010; Butzer, 2012; Gleditsch, 2012). Nonetheless, because no study has provided systematic evidence that climatic events do not influence violence and a large literature provides systematic and consistent quantitative evidence that climatic events alter rates of modern violence (Hsiang and Burke, 2012; Hsiang, Burke and Miguel, 2013), it is *likely* that climate change will alter some patterns of human conflict and insecurity.

The effect of climate change on conflict and insecurity has the potential to become a key risk because the reported magnitude of the climate's influence on security is large. Median estimates from the literature indicate that in modern contexts (1950-2010), the frequency of interpersonal violence rises roughly 4% and the frequency of intergroup conflict rises 12% for each standard deviation change in annual conditions towards warmer temperatures or more extreme rainfall (Hsiang, Burke and Miguel, 2013). Because annual temperatures around the world are expected to rise at least two standard deviations (as measured over 1950-2008) above temperatures in 2000 by 2050, [WG1 Section *11.3.2.1.2*] (Hsiang, Burke and Miguel, 2013), there is potential for large changes to global patterns of personal violence, group conflict and social instability in the future. Social, economic and political changes which

might mitigate or exacerbate this potential impact are discussed in Chapter 12.
It is *likely* that socio-economic, political or technological advancements may cause future populations to respond to their climate somewhat differently than modern populations, however the estimated influence of the global climate on rates of conflict is sufficiently large in magnitude that these advancements may need to be dramatic in order to offset the potential influence of future climate changes. For example, Hsiang *et al*. (2011) estimate that the historical impact of a three-degree Celsius warming in the equatorial Pacific is sufficiently large that offsetting its impact on annual civil conflict risk for a low-income country requires raising average incomes by more than a factor of ten.

19.4.2.3. Species Range Shifts: Consequences

One of the main adaptations of species to climate extremes and climate change is shifting to more climatically suitable areas. The resulting losses, gains, and changes in species abundance are having, and will continue to have, profound impacts on ecosystem functioning, posing risks to the services they provide (Dossena et al., 2012; Millennium Ecosystem Assessment, 2005), including those related to climate regulation (Wardle et al. 2011). One example of a key impact would be the warming-driven expansion and intensification of Mountain pine beetle (*Dendroctonus* ponderosae) outbreaks in North American pine forests. These have already caused both declines in timber harvest and led to the conversion of these forests from net carbon sinks to large net carbon sources (Kurz et al., 2008), especially from forest fires. Potential key vulnerabilities would be the projected impacts of range shifts on important resource species (e.g. marine fishes), where catch potential is predicted to increase by 30-70% in high latitude regions but decline by 40% in the tropics (where fish are important sources of protein) by 2055 (Cheung et al. 2010)), as well as new introductions of diseases to people, livestock, crops and native species (Chakraborty & Newton, 2011; Jepsen et al., 2008; Gale et al., 2009; Lafferty, 2009). Newly arrived species may prey on, outcompete or hybridize with existing biota, becoming weeds or pests in agricultural systems (Thuiller 2007; Walther et al. 2009; Chown et al. 2012). The potential emergent risks and ecological implications of species reshuffling into novel, no-analogue communities largely remain, as yet, unknown (Root & Schneider 2006; J. W. Williams & Jackson 2007).

Current legal frameworks and conservation strategies face the challenges of untangling desirable species range shifts from undesirable invasions (Webber and Scott, 2011), and identifying circumstances when movement should be facilitated versus inhibited. New agreements (e.g., Memoranda Of Understanding) may be needed recognizing climate change impacts on existing, new, or altered national trans-boundary migration, for example under the Convention of Migratory Species (UNEP/CMS, 2006). As target species and ecosystems move, protected area networks may become less effective for conserving them, necessitating re-evaluation and adaptation, including possible addition of sites, particularly those important as either 'refugia' or migration corridors (Warren et al in press, Willis & Bhagwat 2009; Hole et al. 2011; Hannah 2011). Assisted colonisation – moving individuals or populations from currently occupied areas to locations with higher probability of future persistence – is emerging as a potential conservation tool for species unable to track changing climates (Hoegh-Guldberg et al. 2008; Richardson et al. 2009; Thomas 2011). The value of these approaches, however, it contested and implementation is very limited (Loss et al. 2011). *Ex situ* collections (i.e. in zoos, botanical gardens, and seed and gene banks) have often been put forward as fall-back resources for conserving threatened species, yet the expense and the relatively low representation of global species and genetic diversity (Wyse-Jackson 2002; FAO 2010; Conde et al. 2011) minimizes the effectiveness of this technique.

19.4.3. Indirect, Trans-Boundary, and Long-Distance Impacts of Mitigation Measures

Mitigation, too, can have unintended consequences beyond its boundaries, which may affect natural systems and/or human systems (19.4.3.1, 19.4.3.2). If mitigation involves a form of land use change, then regional implications can ensue in the same way as they can for adaptation (see 19.3.2.5).

19.4.3.1. Effects on Biodiversity

Mitigation can reduce direct climate change impacts on biodiversity (Warren *et al*., 2012, ten Brink *et al*., 2010). However, especially in tropical regions, impacts on biodiversity (potential species loss) as a result of widespread habitat conversion for biofuel production could offset biodiversity impact reductions resulting from reduced levels of climate change attributable to use of such biofuels (ten Brink *et al*. 2010, Sala *et al*. 2009). Second generation bioenergy, or use of degraded land, would have reduced impacts on ecosystems (Searchinger *et al*. 2008, van Oorschot *et al*., 2010). It is possible to further offset losses due to land use change by increasing agricultural productivity, thus reducing some of the competition for land use. Tropical forests, in particular, can also be preserved under biofuel cropping strategies if the climate mitigation policy applied incorporates an economic price for emissions from land use change (Thomson *et al*., 2010). Increasing oil-yield efficiency of major biodiesel feedstocks could also reduce land pressures. See also 19.3.2.2.

Climate change mitigation through 'clean energy' substitution can have negative impacts on biodiversity. For example, poorly designed and sited wind farms (both on- and off-shore) can have population level impacts on some bird and bat species. However, these impacts can be reduced (especially on birds) and off-shore wind farms have been shown to have a positive impact on demersal fisheries (Wilhelmsson *et al*., 2006). The same can also be said for many of some other renewable energy proposals (e.g., wave energy, tidal barrages, and tidal turbines). Attention to siting and monitoring can decrease potentially large-scale negative ecological and socioeconomic impacts while maximizing positive ones. For example, the U.S. Government performed an intensive study of suitable sites for solar power on public lands in the western U.S. The end result opened 285,000 acres of public land for large-scale solar deployment while blocking development on 78 million acres to protect "natural and cultural" resources. In the case of hydropower, the construction of capital-intensive large hydroelectric dams, affects both terrestrial ecosystems within the hydroelectric reservoir and surrounding areas and the aquatic ecosystems far up- and downstream along the river system (World Commission on Dams, 2000). These impacts on biodiversity may include high deforestation rates in the surrounding landscape due to (i) new roads, power transmission lines, and new settlements to accommodate the large migrant workforce involved in building large dams, (ii) mass tree mortality within low-elevation inundated areas, and (iii) discontinuity of upstream fish migrations (World Commission on Dams, 2000; Anderson *et al*. 2006; Bertham and Goulding 1997; Finer and Jenkins 2012). In all cases, low-lying forests and savannas are disproportionately affected by the direct and indirect impacts of building and maintaining a large dam. The biodiversity losses from large dams are particularly large relative to benefits of the dams in relatively flat lowland areas where the ecological effect of dams — which is often expressed as the total inundated area (km^2) per unit of electricity produced (MW/yr) — tends to be very high. In addition to a wide range of ecological impacts, local indigenous populations are sometimes displaced from their traditional territories within the reservoir area and immediate vicinities — in direct contradiction of the UN Declaration of Indigenous Rights (UN General Assembly 2007). In sum, there is a wide range of detrimental biodiversity, carbon storage and socioeconomic consequences of augmenting hydropower generation through large dam construction, especially in tropical countries.

19.4.3.2. Effects on Human Systems

Mitigation strategies will have a range of effects on human systems, dependent on the type of mitigation strategy as well as the type of human system. Even within a particular mitigation strategy, effects may vary considerably. Reforestation that properly mimics existing forest ecosystems in structure and composition would potentially benefit human systems by stabilizing micro-climatic variation (Canadell and Raupach, 2008). It would also provide numerous benefits from the sustainable harvest of non-timber forest products (NTFPs) for food, medicine and other marketable commodities (Guariguata *et al*., 2010). However, there is a generally longer time frame and greater expense involved in recreating a diverse forest system. As mitigation measures are implemented in the future, the short-term benefits from planting monoculture stands of tree species most beneficial for climate mitigation may be given greater weight than more complex reforestation efforts. In this scenario, human systems may still benefit from improved local climate effects but not benefit from the utilization of species in a diverse forest system (Guarigata *et al*., 2010). A current example of this approach is found in China where the world's largest reforestation effort has led to dense monoculture stands of fast growing tree species through the Three North Shelterbelt Development Program (Zhang and Song, 2005). Afforestation (foresting an area that was historically not forested) creates a

similar set of costs and benefits. In both reforestation and afforestation, land tenure and ownership becomes an issue for human systems (Unruh, 2008). Relocation of human populations from agricultural lands in order to reforest would have negative consequences for those affected unless clear and thoughtful strategies are implemented. In this scenario, it would be necessary to "mitigate" the effects on human systems caused by climate mitigation. Efforts to preserve existing forests would have an overall benefit for human systems since over the long term, the costs to maintain an intact forest are much lower than the cost to restore a forest. Human populations utilizing NTFPs may continue to benefit as long as such utilization is carefully monitored for sustainability (Newton, 2008).

More generally, mitigation strategies designed to reduce dependence on carbon-intensive fuels present a very different set of circumstances in relation to human systems. The development of alternative and renewable energy sources will have significant economic and market effects which could influence food prices (see also 19.4.1). Some scenarios suggest a rise in energy costs solely due to the lower flexibility of renewable energy resources compared to fossil fuels, which would in turn affect prices in the energy-dependent agriculture sector. This would especially affect marginal populations who already devote a considerable portion of their household income to food (Hymans and Shapiro, 1976).

19.5. Emerging Risks

Emergent risks discussed above are related to multiple interacting systems and stressors (section 19.3) or to indirect and long-distance impacts (section 19.4). However, an additional set of risks has emerged in the literature recently, related to diverse aspects of climate change, including the impacts of a large temperature rise, ocean acidification and other direct consequences of CO_2 increases, and the potential impacts of geoengineering implemented as a climate change response strategy.

19.5.1. Risks from Large Global Temperature Rise >=4°C Above Pre-Industrial Levels

Most climate change impact studies have been based on climate change scenarios corresponding to global mean temperature rises of up to 3.5°C relative to 1990 (or 4°C above pre-industrial levels) (Parry *et al.,* 2004; Hare, 2006; Warren *et al*., 2006; Fischlin *et al*., 2007; Easterling *et al*., 2007). In this section, all warming scenarios are relative to pre-industrial levels unless otherwise noted. Recently the potential for larger amounts of warming has received increasing attention in the literature, motivated by the possibilities that future radiative forcing could be higher than typically considered and that positive feedbacks between climate and the carbon cycle could be strong (Betts et al. 2011; Sanderson et al., 2011). In a 4°C world, the effects of climate change on water resources and ecosystems are projected to become dominant over other drivers such as population increases and land use change (Arnell et al 2009, Bellard et al 2012).

Under a warming of 5°C, 30-40% of the global population are projected to be exposed to water stress (Gerten *et al*., submitted) under the A2 population projections. Similarly, 20-30% more people globally are expected to be affected by increased water stress, compared to those projected affected in a 2°C world (Arnell *et al*., 2011). Annual runoff is projected to fall by 40-80% variously across the Danube, Mississippi, Amazon and Murray Darling river basins, and to increase by 40% in the Nile and Ganges (Fung *et al*., 2011). The total 'drought disaster affected area' is expected to increase from 15% today to 44+/-6% in a range of scenarios which include some that reach 4°C by 2100 (Li et al 2009).

Globally, agricultural production is expected to decline in mid-high latitudes once local temperature rise exceeds 3°C (IPCC AR4) (and for lower temperature rise in the tropics), corresponding to global temperature rise below 4°C). Beyond 4°C there is high risk of marked yield loss even at high latitudes (Rotter et al. 2011, section 23.4.1). Ciscar et al (2011) estimated that a 3.5°C warming globally could reduce crop yields in Europe by 10%. There is concern that current crop modelling efforts cannot capture the non-linear responses shown by crops in response to past temperature variability, which led Schlenker and Roberts (2009) to project crop yield losses of 63-82% under 4°C warming. Today's crop models may be unable to capture well the impacts of large temperature rise (Rotter *et al.,* 2011) and also omit the concomitant effects of projected increase in pests and disease.

Under a 4°C warming, biomes in temperate zones are projected to be significantly affected, whereas under 2°C warming the effects are projected to affect mostly polar and tropical regions. Humid tropical forests are projected to lose 75% of their current extent (Zelazowski *et al*., 2011). Poleward latitudinal biome shifts of up to 400km are possible in a 4°C world (Gonzalez *et al*., 2010). Twelve to thirty-nine percent of the Earth's surface is projected to experience a novel climate (Williams *et al*., 2007) whilst on 10-48% of the Earth's surface, current climates will disappear locally as, for example, isotherms rise up mountains or towards coasts and are lost in a 4°C world. This includes highly biodiverse regions such as the Himalayas, Mesoamerica, E and S Africa, the Philippines and Indonesia. , Tropical and temperate eco-regions of exceptional biodiversity projected to experience monthly mean temperatures that deviate by between two and four standard deviations from those of the 1990s (Beaumont *et al*., 2011). Concomitantly, the climate envelopes of 60% of plants and 33% of animals are projected to shrink by more than 50% (Warren *et al*., in press.). Large climate change induced shifts in fire regimes are expected in ecosystems at 4°C. Widespread coral reef mortality is expected at 4°C, since this corresponds to CO_2 increases causing increase of about 150% in ocean acidity (World Bank 2012). Well below this threshold, at 3°C, coral reefs are expected to start to dissolve (see section 5.4.2.4). Hypoxic zones may be seen in the ocean, reducing the habitat for fish such as tuna (Stramma *et al.,* 2011). Together, these effects all point to a very extensive loss of biodiversity in a 4°C world (*high evidence, high confidence*), with concomitant loss of valuable and essential provisioning, regulating, supporting and cultural ecosystem service (*medium evidence, high confidence*). Loss of ecosystem services has negative economic and physical consequences for human agricultural and urban systems and upon human physical and mental health (Chivian and Bernstein, 2008).

An additional 250000 people are projected to be affected by river flooding in Europe in a 3.5°C world in the 2080s (Ciscar *et al*., 2011) assuming *no* population growth from today. A sea level rise of 0.5 to 1 m is *likely* by 2100 in a 4°C world (AR5 WGI Table 13.5) and would result in the inundation of many small island states.

Emerging risks associated with warming greater than 4°C above pre-industrial include the potential exceedance of human physiological limits in some areas for a global temperature rise of 7°C above pre-industrial (Sherwood and Huber, 2011); and reductions in labor productivity e.g., loss of 5% in economic output in a 6°C world (Roson and Mensbrugghe, 2010). Extreme heat waves such as that experienced in Russia in 2010 can become typical of a normal summer in a 4°C world (World Bank, 2012).

The following non-linear earth system responses would be expected to be triggered for a persistent 4°C temperature rise (a) Amazon dieback (Lenton *et al*. 2008; Malhi *et al*. 2009; Salazar and Nobre 2010) (*medium confidence*). (b) Eventual, irreversible loss of the Greenland Ice Sheet (see section 19.6.3.6, *high confidence*) (c) More widespread terrestrial carbon loss due to climate-carbon cycle feedback (AR5 WGI Ch. p.6-5, *very likely*). The chance of triggering other non-linear responses such as the collapse of the West Antarctic Ice Sheet is also greatly increased (see section 19.6.3.6).

Sub-Saharan Africa is identified as a multi-impacts hotspot in a 4°C world, with projected loss of 25-42% of plant species (Midgley and Thuiller, 2011), loss of 35% of cropland (Arnell *et al*., 2009), major reductions in growing season length (Thornton *et al*., 2011), increased risks of hunger (Sissoko *et al*., 2010, Mougou et al 2010) and areas where the probability of malaria transmission rises by 50% (Beguin, 2011). In the Upper Nile basin in Uganda, increased potential evapotranspiration as occurring under at high global temperature increases of 4°C or more is projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010; section 3.4.6).

More generally, simulations of climate change impacts at 4°C and above show greater and more significant impacts than at lower levels of global temperature rise (*medium evidence, high confidence*). The large projected increases in populations exposed to water stress, fluvial and coastal flooding, the potential for crop yield losses, and the projected widespread disruption of ecosystem function and services, alongside projected extinction of a significant proportion of the earth's biodiversity, would create large aggregate impacts of climate change on society generally and on the global economy (see 19.6.3.5). Furthermore, these effects will interact, risking a cascade of impacts

which may induce the crossing of tipping points in socio-ecological systems in many areas (Warren *et al*., 2011; 19.7.5), potentially increasing the scope of migration, which is sometimes disruptive, or conflict (19.4.3, 12.4, 12.5).

[INSERT TABLE 19-2 HERE
Table 19-2: Key risks from large temperature rise.]

19.5.2. Risks from Ocean Acidification

Ocean acidification is defined as "a reduction in pH of the ocean over an extended period, typically decades or longer, caused primarily by the uptake of carbon dioxide from the atmosphere" (WG1 Ch. 3; see also WG2 Glossary). It is a physical impact resulting from CO_2 emissions that poses emerging risks to marine ecosystems and the societies that depend on them. Ocean acidification impacts are a relatively new research area, and the potential for associated risks to become key is magnified by the fact that it is a global phenomenon and, without a decrease in atmospheric CO_2 concentration, it is irreversible on century timescales.

It is *virtually certain* that ocean acidification is occurring now (Dore *et al*., 2009; Byrne *et al*., 2010; Table 3.2 of WG1 Ch. 3) and will continue to increase in magnitude as long as the atmospheric CO_2 concentration increases (National Academy of Sciences, 2010). Risks to society and ecosystems result from a chain of consequences beginning with direct effects on biogeochemical processes and organisms and extending to indirect effects on ecosystems, ecosystem services, and society (Figure 19-3). The degree of confidence in assessing risks decreases along this chain due to the complexity of interactions across these scales and the relatively small number of studies available for quantitative risk assessment.

[INSERT FIGURE 19-3 HERE
Figure 19-3: The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. Confidence in quantifying these effects (as summarized from WG2 Chapter 6) decreases with each step along the pathway.]

Most studies have focused on the direct effects of ocean acidification on marine organisms and biogeochemical processes. The overall effects on organisms can be assessed with *medium confidence* (WG2 Ch. 6), but this varies widely with process and organism, e.g., *medium confidence* that the increase in dissolved CO_2 will cause an increase in primary production, *low to medium confidence* that nitrogen fixation rates will be stimulated (depending on organism); *low to high confidence* that calcification rates will decrease (depending on organism); and *high confidence* that a decrease in pH will reduce the thermal tolerances of organisms (WG2 Ch. 6). Ocean acidification can also affect the availability of iron for marine photosynthesis and the chemical state and toxicity of some metals, although these effects are currently poorly understood (Millero *et al*., 2009, Hoffmann et al., 2012).

Far fewer studies have assessed the impacts on ecosystems and ecosystem services (Cooley, 2012), and most of these studies have focused on the economic impacts on fisheries (Cooley and Doney 2009; Cooley *et al*. 2011; Narita *et al*. 2012). For example, changes in overall availability and nutritional value of desired mollusk species could impact economies (Narita *et al*.; 2012) and food availability (Cooley and Doney, 2009; Cooley 2012). Figure 19-4 illustrates how evidence can be used to assess these risks, leading to the conclusion that risks to ecosystem services related to marine calcification are high and those related to nitrogen fixation are more uncertain. Changes in coral calcification are *likely* and we judge the potential magnitude of impacts to some ecosystem services (e.g., the role of coral reefs in supporting habitats, provisioning of fish, regulating shoreline erosion, and tourism) to be *medium to high*. Studies document significant changes in community composition, biodiversity, calcification rates, and recruitment of corals and other calcifiers caused by natural carbon dioxide seeps that produce acidification consistent with that expected to result from an atmospheric CO_2 concentration of 750 ppmv (Hall-Spencer *et al*., 2008; Fabricius *et al*., 2011). If such changes are representative of future changes to benthic calcifying systems, then the ecosystem services they provide will in turn be degraded. The loss of coral reef structure, for example, has been linked to changes in abundance and diversity of reef fishes (Jones *et al*. 2004; Wilson *et al*. 2012; Chong-Seng, *et al*. 2012).

[INSERT FIGURE 19-4 HERE
Figure 19-4: Risks of ocean acidification to ecosystems services through two effects on biogeochemical processes: (1) reductions in calcification rates (of corals) and (2) increases in nitrogen-fixation rates. Assessments are based on the estimated *likelihood* that the process will be affected by ocean acidification (horizontal axis) and the *magnitude* of the impacts on associated ecosystem services (vertical axis) should the process be affected. Heights and widths of boxes indicate the range of uncertainty in the magnitude of impacts on ecosystem services and likelihood of change in the process, respectively. Heights are greater than widths due to the lower confidence in responses of ecosystems and their services (Figure 19-3). Judgments are based on impacts expected with atmospheric CO_2 levels of 2-3x preindustrial levels (560-840 ppmv). This figure is meant to be broadly illustrative: with sufficient information Low, Medium, and High magnitudes of impacts would be defined quantitatively. The shading of the box represents the risk (*likelihood* x *magnitude*) to ecosystem services with the dashed contour showing the line of equal risk; the area above and to the right of this line is broadly indicative of key risks. Thus, the reduction in calcification due to ocean acidification is already considered a key risk to some ecosystem services, while the limited evidence regarding the nitrogen fixation response and its impacts implies that it may or may not become a key risk as uncertainty is reduced.]

In contrast, several laboratory studies show that nitrogen fixation rates increase under ocean acidification conditions (WG2 Ch. 6), but there is limited evidence for this in field studies and the magnitude of the impacts to ecosystem services (e.g. nitrogen cycling) is largely unknown, so that the risk of this impact is difficult to quantify.

19.5.3. Risks from CO_2 Health Effects

There is increasing evidence that the impacts of elevated atmospheric CO_2 on plant species will affect health via two distinct pathways: the increased production and allergenicity of pollen and allergenic compounds, and the nutritional quality of key food crops. The evidence for these impacts on plant species is increasingly robust and recent evidence in the public health literature points to the potential for these risks to be sufficiently widespread in geographical scope and large in their impact on human health to be considered an emerging risk.

Climate change is expected to alter the spatial and temporal distribution of several key allergen-producing plant species (Shea, 2008), and increased atmospheric CO_2 concentration, independent of climate effects, has been shown to stimulate pollen production(Rasmussen, 2002; Clot, 2003; Galán *et al.*, 2005; Garcia-Mozo *et al.*, 2006; Ladeau and Clark, 2006; Damialis *et al.*, 2007; Frei and Gassner, 2008). Ziska *et al.* (2000, 2003, 2012) found an association between elevated CO_2 concentrations and temperature with faster growing and earlier flowering ragweed species (*Ambrosia artemisiifolia*) along with greater production of ragweed pollen (Wayne *et al.*, 2002; Singer *et al.*, 2005; Rogers *et al.*, 2006) leading, in some areas, to a measurable increase in hospital visits for allergic rhinitis (Breton et al. 2006). Experimental studies have shown that poison ivy, another common allergenic species, responds to atmospheric CO_2 enrichment through increased photosynthesis, water use efficiency, growth, and biomass. This stimulation, exceeding that of most other woody species, also produces a more potent form of the primary allergenic compound, urushiol (Mohan *et al.,* 2006).

While climate change and variability is expected to affect crop production (see Chapter 7), emerging evidence suggests an additional stressor on the food system: the impact of elevated levels of CO_2 on the nutritional quality of important foods. A prominent example of the effect of elevated atmospheric CO_2 is the decrease in the nitrogen (N) concentration in vegetative plant parts as well as in seeds and grains and, related to this, the decrease in the protein concentrations (Cotrufo *et al.*, 1998; Taub *et al.*, 2008; Wieser *et al.*, 2008). Experimental studies of increasing CO_2 to 550 ppm demonstrated effects on crude protein, starch, total and soluble B-amylase, and single kernel hardiness, leading to a reduction in crude protein by 4 to 13% in wheat and 11 to 13% in barley (Erbs at el, 2010). Other CO_2 enrichment studies have shown changes in the composition of other macro- and micronutrients (Ca, K, Mg, Fe, Zn) and in concentrations of other nutritionally important components such as vitamins and sugars (Idso and Idso, 2001). The declining nutritional quality of important global crops is an emerging risk that has the potential to broadly affect rates of protein-energy and micronutrient malnutrition in vulnerable populations. While this emerging risk has the potential to become key, there is currently insufficient information to assess under what ambient CO_2 concentrations this risk will manifest as key.

19.5.4. Risks from Geoengineering (Solar Radiation Management)

Geoengineering refers to a set of proposed methods and technologies that aim to alter the climate system in order to alleviate the impacts of climate change (WG2 Glossary; IPCC, 2012b). It is distinct from mitigation, in that mitigation aims to reduce or prevent actions that would change the climate, such as emissions of gases and particles and changes to the land surface, while geoengineering involves deliberate changes to the climate system itself. The main benefit of geoengineering would be the reduction of climate change that would otherwise occur, and the associated reduction in impacts (Pongratz *et al.*, 2012; section 19.7.1). Here we focus on risks, consistent with the goal of this chapter.

Geoengineering is an emerging risk both because it poses risks to society and ecosystems that could be large and widespread and because, although it is not a new idea (e.g., Rusin and Flit, 1960; Environmental Pollution Panel, 1965; Budyko, 1974, and a long history of geoengineering proposals as detailed by Fleming, 2010), it has received increasing attention in the recent scientific literature, stimulated in part by suggestions that nations might consider geoengineering solutions to global warming in light of the absence of comprehensive global mitigation policy (Crutzen, 2006; Wigley, 2006). Geoengineering has come to refer to both carbon dioxide concentration reduction (CDR, discussed in detail in AR5 WG I, Chapter 6) and solar radiation management (SRM; Shepherd et al., 2009; Lenton and Vaughan, 2009; discussed in detail in AR5 WG I, Chapter 7), and both are discussed in AR5 WG I, FAQ 7.3. These two different approaches to climate control raise very different scientific (e.g. Izrael *et al.*, 2009), ethical (Morrow et al., 2009; Preston, 2013) and governance issues (Lloyd and Oppenheimer, 2012). Many approaches to CDR are better defined as mitigation than as geoengineering (AR5 WGI, Chapter 6), and CDR is thought to produce fewer risks than SRM if the CO_2 can be removed from the atmosphere efficiently and stored safely (WGI Chapter 6; Royal Society 2009). For these reasons, in addition to the more substantial recent literature on SRM's potential impacts on physical (see WGI, Chapter 7), social and ecological systems, we only address SRM in this section.

Various SRM schemes have been suggested, and are described in detail in AR5 WG I, Chapter 7. However, studies of impacts on society and ecosystems have been based on stratospheric aerosols and marine cloud brightening, two approaches that seem to have the potential to produce large-scale, effective and inexpensive cooling (Salter *et al.*, 2008; Lenton and Vaughan, 2009; McClellan *et al.*, 2012). Observations of volcanic eruptions, frequently used as an analogue for SRM (Robock *et al.*, 2013), indicate that while stratospheric aerosols can reduce the global average surface air temperature, they can also produce regional drought (e.g., Oman *et al.*, 2005; Trenberth and Dai, 2007), lead to famine (in the pre-industrial period; Oman *et al.*, 2006), cause ozone depletion (Solomon, 1999), and reduce electricity generation from solar generators that use focused direct sunlight (Murphy, 2009). Climate modeling studies confirm the risk of ozone depletion (Tilmes *et al.*, 2008, Rasch *et al.* 2008), and some find that stratospheric geoengineering would reduce summer monsoon rainfall relative to current climate in Asia and Africa, potentially threatening the food supply for billions of people (Robock *et al.*, 2008; Jones *et al.*, 2010), but others find different regional patterns (Rasch *et al.*, 2008).

Use of SRM can also pose risks as a climate change response strategy, most importantly due to the risk of rapid climate change if it fails or is halted (Wigley, 2006; Matthews and Caldeira, 2007; Robock et al., 2008; WGI Ch 7), which would be *very likely* to have large negative impacts on ecosystems (Russell et al., 2012) and could offset the benefits of SRM (Goes et al., 2011). Also, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict. Since SRM appears to be very inexpensive (Robock *et al.*, 2009; McClellan *et al.*, 2012) geoengineering could be undertaken by non-state actors or by small states acting on their own (Lloyd and Oppenheimer, 2012), potentially producing global or regional conflict (Robock, 2008b).

19.6. Key Vulnerabilities, Key Risks, and Reasons for Concern

In this section, we present key vulnerabilities, key risks, and emergent risks that have been identified by many of the chapters of this report based on the material assessed by each. We then discuss dynamic characteristics of

vulnerability and risk, features which are influenced by development pathways in the past, present and future. These illustrative examples of climate-related hazards (or non-climatic stressors), key vulnerabilities, key risks and emergent risks in Table 19-3 are selected from a larger number provided by the chapters of this report. The table (19-3) indicates how these four categories are related as well as how they differ. The table also provides information on how key risks actually develop due to changing climatic hazards and vulnerabilities. This knowledge is an important prerequisite for effective adaptation and risk reduction strategies that have to address climate related hazards, non-climatic stressors and various vulnerabilities that often interact in complex phenomena and change over time. In addition to these examples, key risks may also arise from moderate vulnerability interacting with a very large physical impact.

19.6.1. Key Vulnerabilities

Several of the risks discussed in this and other chapters and noted in Table 19-3 arise because vulnerable people must cope and adapt not only to changing climate conditions, but to multiple, interacting stressors simultaneously (see 19.4), which means that effective adaptation strategies would address these complexities and relations.

19.6.1.1. Dynamics of Vulnerability

This sub-section deals with the meaning and the importance of dynamics of vulnerability, while section 19.6.1.3 assesses recent literature and data regarding observed trends of vulnerability mostly at a global or regional scale. The literature provides increasing evidence that structures and processes that determine vulnerability are dynamic and spatially variable (IPCC, 2012; and section 19.6.1.3). SREX states with *high confidence* that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic, thus varying across temporal and spatial scales due to influences of and changes in social, economic, demographic, cultural, environmental and governance factors (IPCC, 2012, p. 7).

Examples of such dynamics in exposure and vulnerability encompass, e.g. population dynamics, such as population growth (Table 19-3, Entry 1, Chapter 19) and increasing exposure of people and settlements in low lying coastal areas or flood plains in Asia (see Nicholls and Small 2002; Levy, 2009; Fuchs *et al*., 2011; IPCC, 2012; Peduzzi *et al*., 2012). Also, demographic changes, such as aging of societies, have a significant influence on vulnerability to heat stress (see Staffogia *et al*., 2006; Gosling *et al*., 2009). Changes in poverty or socio-economic status, race-ethnicity compositions as well as age structures had a significant influence on the outcome of past crises and in addition were modified and reinforced through disasters triggered by climate and weather related hazards. Cutter and Finch (2008) found that social vulnerability to natural hazards increased over time in some areas of the United States due to changes in socio-economic status, race-ethnicity composition, age, and density of population. Changes in the strength of social-networks (e.g., resulting in social isolation of elderly) and physical abilities to cope with such extreme events modify vulnerability (see e.g. Khunwishit, 2007).

In some cases human vulnerability might also change in different phases of crises and disasters. Hence, the factors that might determine vulnerability before the crises or disaster (drought crises, flood disaster) might differ from those that determine vulnerability thereafter (post-disaster and recovery phases). Disaster response and reconstruction processes and policies can modify vulnerability e.g. of coastal communities (Birkmann and Fernando, 2008; Birkmann, 2011b). A comprehensive assessment of vulnerability would account for these dynamics by evaluating long-distance impacts (e.g., resulting from migration or global influence of regional crop production failures following floods) and multiple-stressors (e.g. recovery policies after disasters) that often influence dynamics and generate complex crises and even emergent risks.

19.6.1.2. Differential Vulnerability

Wealth, education, race, ethnicity, religion, gender, age, class/caste, disability, and health status exemplify and contribute to the differential vulnerability of individuals or societies to climate and non-climate related hazards (see

IPCC, 2012). Differential vulnerability is, for example, revealed by the fact that people and communities that are similarly exposed face different levels of harm, damage and loss as well as success of recovery (see Birkmann, 2006). The uneven effects and uneven suffering of different population groups and particularly marginalized groups is well documented in various studies (Bohle *et al*., 1994; Kasperson and Kasperson, 2001; Thomalla *et al*., 2006; Birkmann, 2006; Sietz *et al*., 2011). Factors that determine and influence these differential vulnerabilities and exposure patterns to climate-related hazards encompass among other factors e.g. race and ethnicity(Fothergill *et al*., 1999; Elliott and Pais, 2006; Cutter and Finch, 2008), socioeconomic class (O'Keefe *et al*., 1976; Peacock, 1997; Ray-Bennett, 2009), gender (Sen, 1981), age (Jabry, 2003; Ben, 2006; Bartlett, 2008) as well as migration experience (Cutter and Finch, 2008) and homelessness (Wisner, 1998; IPCC, 2012a). These differential vulnerabilities are often attributed to specific populations at a particular scale using quantitative or qualitative assessment methodologies (Cardona, 2006; Cardona, 2008; Birkmann *et al*., 2013). Groups that are marginalized, particularly due to gender or wealth status or ethnicity, are differentially affected by physical impacts of climate change in terms of both gradual changes in mean properties and extreme events (e.g., Neal and Phillips, 1990; Enarson and Morrow, 1998; Neumayer and Plümper, 2007; Sietz *et al*., 2011b). Studies emphasize that vulnerability in terms of gender is not determined through biology, but in most cases by social structures, institutions and rule systems; hence women and girls are often (not always) more vulnerable due to the fact that they are marginalized from decision making or experience discrimination in development and reconstruction efforts (Fordham, 1998; Houghton, 2009; Sultana, 2010; IPCC, 2012a).

19.6.1.3. Trends in Vulnerability

Vulnerability and exposure of societies and social-ecological systems to physical impacts of climate change are dynamic and depend on economic, social, demographic, cultural, institutional, and governance factors (see IPCC, 2012, p.7). Population growth, rapid and unsustainable urban development, international financial pressures, increases in socioeconomic inequalities, failures in governance (e.g. corruption), and environmental degradation are trends that modify vulnerability of societies and communities (Maskrey, 1993a; Maskrey, 1993b; Maskrey, 1994; Mansilla, 1996; Maskrey, 1998; Cannon, 2006) at different scales. Consequently, many of the factors that reveal and determine differential vulnerability, such as socio-economic status, wealth, poverty, age, health conditions or migration experience and governance processes (see 19.6.1.2) are dynamic, often changing over time in terms of their spatial distribution. Consequently, identifying, assessing and reducing vulnerability requires accounting for such dynamics and changes in vulnerability over time, e.g. due to different socio-economic development trends and policies. The following section outlines observed trends in vulnerability according to different thematic dimensions (socio-economic, environmental, institutional), within the constraint that data for assessing such trends in vulnerability is still fragmentary and much of it only recently emerging.

19.6.1.3.1. Trends in socioeconomic vulnerability

Poverty is arguably one of the key factors determining vulnerability of societies to climate change and extreme events. For example, there is *high confidence* that drought risk – particularly in sub-Sahara Africa - is intimately linked to poverty and rural vulnerability (see GAR, 2011, p. 62; WRI, 2012; World Bank, 2010). Hence, the risk of loss of livelihoods and harm due to droughts is heavily influenced by the poverty patterns and livelihoods of communities exposed to drought, e.g. in Africa or Asia. Restocking by poor pastoralists' households in rural areas in Africa after a drought may take several years due to limited financial resources (see Chapter 13). Recent global studies for 119 countries found that at the international level there is a clear decrease in global poverty over the past six years (Chandy and Gertz, 2011). The number of poor people globally fell by nearly half a billion people, from over 1.3 billion in 2005 to under 900 million in 2010. This trend is expected to continue; hence at a global level most projections show a decreasing level of poverty and extreme poverty at the global scale (e.g. Chandy and Gertz 2011; Hughes *et al*., 2009). While the poverty rate at the global level is decreasing and now accounts for approximately 16 percent of the total global population (in 2010), regional differences are significant, as are differences between emerging and least develop economies. As a result, there is a growing climate-related risk in some regions due to chronic poverty. For example, the highly drought exposed region sub-Sahara Africa still has approximately 47% of its population living in poverty (poverty headcount ration at $1.25 per day; see World Bank

2012) and already has been defined as a global risk hotspot (see WRI, 2011; WRI, 2012). Moreover, even national-level poverty statistics provide little information about the actual distribution of poverty in a specific country, for example regarding rural-versus-urban areas or different ethnic and age groups. Income distribution trends show significant increases in inequality in some countries in Africa and particularly in Asia, such as in China, India, Indonesia and Bangladesh (World Bank, 2012). In Asia and South East Asia (e.g, China, Indonesia or Bangladesh) this trend overlaps with climate impact hotspots in terms of people currently exposed to floods and tropical cylcones as well as sea-level rise (Förster *et al*., 2011; Peduzzi *et al*., 2012; IPCC, 2012a). Assessing vulnerability in these countries requires in-depth analysis of trends and distribution patterns of poverty, income disparities and exposure of people to changing climatic hazards.

New socio-economic vulnerabilities are emerging in some countries, for example in developed countries, where the impoverishment of the middle class can be observed or where poverty is newly increasing among, for example, elderly people that have limited physical means to cope with climatic hazards.

Health conditions of individuals and population groups affect vulnerability to climate change by limiting capacities to cope and adapt to climate hazards. Although at a global scale the percentage of people undernourished is decreasing (FAO, 2012) and this trend is expected to continue(Hughes *et al*., 2009), the regional and national differences are significant: between 2010-12, 870 million people remained chronically undernourished. Particularly in countries highly exposed to current and projected climate-related hazards, such as droughts in Africa, more than one third of the population is undernourished (FAO, 2012, p. 10; Hughes *et al*., 2009). Moreover, trends in HIV/AIDS, tuberculosis and malaria are also observed in regions that are highly exposed to climatic hazards, such as Africa and South-East Asia. These multi-hazard contexts may require new approaches in climate change adaptation; for example, countries exposed to these health risks often face significant limitations with regard to their health systems(Vitoria *et al*., 2009) as indicated by the incidence of malaria and HIV/AIDS, in some cases of epidemic proportions.

While these trends mainly point to particularly severe vulnerabilities in developing countries, studies regarding extreme heat vulnerability and other challenges related to urbanization also underscore that developed and industrialized countries face increasing challenges to adapt. Extreme heat events, characterized by consecutive days with abnormally high temperatures, are projected to increase in duration, intensity, and extent (AR5 WGI SOD 11.3.2) signaling an emergent public health risk, particularly for urban populations. Advanced age represents one of the most significant risk factors for heat-related death (Bouchama and Knochel, 2002), since beside limited thermoregulatory and physiologic heat-adaptation abilities, elderly also have often reduced social contacts, and higher prevalence of chronic illness and poor health (Khosla and Guntupalli, 1999; Klinenberg, 2002; O'Neill, 2003). The trend towards an aging society, for example in Japan or Germany, therefore increases the vulnerability of these societies to extreme heat stress. Another demographic trend affecting vulnerability to extreme heat is high population growth rates in urban areas, where populations are expected to grow disproportionately over the coming decades (United Nations, 2008). By 2030, approximately 60% of the projected global population of 8.2 billion is expected to live in cities (United Nations, 2006).

19.6.1.3.2. Trends in environmental vulnerability

The environment provides a range of ecosystem services (see e.g. MEA, 2005) that are at risk due to climate change. Societies and communities in some regions that heavily rely on the quality of ecosystem services, such as rural populations dependent on rain fed agriculture where drying is projected (see also Table 19-3, Entries 1 and 2, Chapter 19, and Chapters 7, 13 and 26), are *very likely* to experience increased risk from climate change. Large proportions of the world's rural population – particularly in developing countries – depend on ecosystem services and functions. Although a global overview is still impossible, recent reports (UNDP, 2007; IPCC, 2012a) underscore that a number of current environmental trends threaten human well-being and thus increase human vulnerability (UNEP, 2007). Many communities have suffered considerable losses due to extreme weather events in combination with the degradation of ecosystems and ecosystem services in the past. For example, agricultural productivity, food security, livelihoods and health are being affected by land degradation which often starts with soil sealing with artificial surfaces, erosion, salinization, fire risk, over production, and land fragmentation resulting from both natural

and human-caused changes in climate, soil, vegetation conditions and economic and population pressures (Salvati and Zitti, 2009). In addition, coastal degradation is increasing the exposure of coastal communities to hazards (World Risk Report, 2012) particularly in Asia, e.g., severe degradation of coral reefs. Moreover, the extinctions of species and the loss of biodiversity pose a threat of diminution of genetic pools that otherwise buffer the adaptive capacities of social-ecological systems dependent on these services in the medium and long-run (e.g. in terms of medicine and agricultural production).

19.6.1.3.3. Trends in institutional vulnerability

Institutional vulnerability refers among other issues to the role of governance. Governance is increasingly recognized as a key factor that influences vulnerability and adaptive capacity of societies and communities (Kahn, 2005; WRI, 2011). Severe climate change risks and vulnerabilities to climate change occur in countries that are characterized by failed governance. Countries classified as failed states are often not able to guarantee their citizens basic standards of human security (see Chapter 12) and consequently do not provide support in crises or disaster situations for vulnerable people. At a global level the Failed State Index(Fund for Peace, 2012; Foreign Policy, 2012) as well as the Corruption Perception Index (Transparency International, 2012) are used to characterize institutional vulnerability and governance failure. Trends in the Failed State Index from 2006 to 2011 show that countries with severe problems in the functioning of the state cannot easily shift or change their situation. Countries characterized in the literature as substantially failing in governance or in some particular aspects of governance, such as Somalia and Sudan, Haiti or Pakistan have shown in the past severe difficulties in dealing with extreme events or supporting people that have to cope and adapt to severe droughts, storms or floods (see e.g. Lautze *et al*., 2004; Ahrens and Rudolph, 2006; Khazai *et al*., 2011, p. 30-31; Menkhaus, 2010, p. 320-341). Studies at the global level confirm that countries classified as failed states and affected e.g. by violence are not able to effectively reduce poverty compared to countries without violence (see World Bank, 2011). Hence, governance failure and violence as characteristics of institutional vulnerability have significant influence on socio-economic, and therefore climatic vulnerability. Furthermore, corruption has been identified as an important factor that hinders effective adaptation policies and crisis response strategies (World Risk Report, 2011). There is *high confidence* that unless governance improves in countries with severe governance failure, an increase in risk is likely to occur as a result of climate changes and increased human vulnerability.

19.6.1.4.Risk Perception

Risk perceptions influence the behavior of people in terms of risk preparedness and adaptation to climate change (Burton *et al*., 1993; van Sluis and van Aalst, 2006; IPCC, 2012a). Factors that shape risk perceptions and therewith also influence actual and potential responses (and thus vulnerability and risk) include a) interpretations of the threat, including the understanding and knowledge of the root cause of the problem, b) exposure and personal experience with the events and respective negative consequences, particularly recently (i.e., availability) c) priorities of individuals, d) environmental values and value systems in general (see e.g. O'Conner 1999; Grothmann and Patt, 2005; Weber, 2006; Kuruppu and Liverman 2011). Furthermore, Weber (2010) argues that the perceptions of risk and reactions to such risk and actual events are also shaped by motivational processes (Weber, 2010). In this context people will often ignore predictions of climate-related hazards if those predictions fail to elicit emotional reactions. In contrast, if the event or forecast of such an event elicits strong emotional feelings of fear, people may overreact and panic (see Slovic *et al*., 1982; Slovic, 1993; Slovic, 2000; Weber, 2006). Public perceptions of risks are not solely determined by the "objective" information, but rather are the product of the interaction of such information with psychological, social, institutional, and cultural processes and norms which are partly subjective, as demonstrated in various crises in the context of extreme events (Kasperson *et al*., 1988; Sagiya 2011; Funabashi and Kitazawa, 2012; Hibbs, 2012). Risk perceptions particularly influence and increase vulnerability in terms of false perceptions of security. Finally, it is important to acknowledge that everyday concerns and satisfaction of basic needs may prove more pressing than attention and effort toward actions to address longer-term risk factors e.g., climate change(Maskrey, 1989; Wisner *et al*., 2004; Maskrey, 2011). Rather, peoples' worldviews and political ideologies guide attention toward events that threaten their preferred social order (Douglas and Wildavsky, 1982; Kahan, 2010).

19.6.2. Key Risks

19.6.2.1. Assessing Key Risks

Key risks arise from the interaction of climate-related hazards and key vulnerabilities of societies or communities exposed (see Figure 19-1). Various chapters in this report have dealt with key risks from their specific chapter perspectives. In this regard it is difficult to provide a comprehensive overview. Rather, the following section highlights selected key risks in order to illustrate how key risks develop and why they are seen as fundamental in this report. Based on the input from other chapters and our evaluation of existing literature, the following key risks were identified:

- Risk of increased food insecurity (Chapter 7 and 13)
- Risk of dispossession of land (Chapter 13)
- Risk of loss and degradation of resource bases (e.g. water) and related livelihoods (Chapter 13, 24)
- Risk of increasing infrastructure failures and systemic risk (Chapter 23)
- Risk of serious harm and losses in urban areas, particularly in urban coastal environments (Chapter 26)
- Risk of increased disease burden (Chapter 23)
- Risk of loss of terrestrial, aquatic and marine ecosystems (Chapter 6, 22)
- Risk of species extinction (Chapter 6, 22)

An important common characteristic of all these key risks is that they are determined by influences of hazards due to of changing climatic conditions and climate variability on the one hand and the vulnerability of societies, communities and social-ecological systems, e.g. in terms of livelihoods, infrastructure, and management systems on the other. The following examples should underscore this systematic approach to identifying key risks.

[INSERT TABLE 19-3 HERE
Table 19-3: A selection of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapter 4, 6, 7, 8, 11, 13, 19, 22, 23, 24, 25, 26). Key risks are determined by hazards and stressors interacting with vulnerability and exposure of human systems, infrastructure, and ecosystems or species. The table underscores the complexity of risks determined by various climatic hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, demographic changes or tolerance limits of species and ecosystems which often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g. climate change, urbanization and demographic changes) in combination and in specific development context (e.g. in low-laying coastal zones), can generate new systemic risks that go far beyond existing adaptation and risk management capacities, particularly in highly vulnerable regions.]

Risks of increased food insecurity emerge in various chapters and are linked to changes in e.g. rainfall patterns (temporally and spatially) that creates major stress for rainfed agriculture, particularly for those groups that have little access to alternative modes of income or income earning activities (Chapter 13). In addition, the risk of food insecurity can also be determined by the partial or total breakdown of food distribution and storage processes (Chapter 7) and limited coping and adaptation capacities. These examples also show that key risks might not solely be determined by local conditions, but also national or even regional capacities and limits on ability to manage crop failures and food shortages.

The *risks of dispossession of land* is also closely linked to rural livelihoods and the fact that shifts in energy policies and global markets might constrain access to agricultural land. The lack or limited access to land has contributed to risk when people face extreme events, such as major floods in Pakistan, since land is often used as a resource supporting coping and adaptation processes. Hence the dispossession of and limited access to agricultural land is seen in this report (e.g. Chapter 13) as a key risk in the light of climate change.

Such factors can also increase the *risk of loss of livelihoods*. Overall, there is *high confidence* that the risk of loss of livelihoods is high for people in low-laying coastal zones as well as for people engaged in rain-fed agriculture in developing countries and countries in transition due to changes in climatic conditions as well as socio-economic structures. These changes are already observed in large Delta regions, such as the Mekong Delta, where a strong migration towards urban areas is taking place due to socio-economic challenges farmers face as well as environmental changes such as salinization, saltwater intrusion and flooding linked to sea level rise.

Key risks identified in this report also encompass phenomena that are related to urban areas and infrastructure in developed and developing countries such as the *risks of increasing morbidity and infrastructure failure* as well as *new systemic risks*. In the context of extreme weather events, risks in the transport, energy and health sector are identified that emerge due to the interdependency of the different sectors, e.g. on energy supply (see Chapter 23). The potential for power shortages and the low adaptive capacity of power supply systems adds to the risk of heat stress during extreme events. These phenomena have been observed in both developing and developed countries. In this regard high temperature extremes in combination with ongoing urbanization trends, aging populations and vulnerable infrastructure increase the potential for infrastructure failure and the risk of morbidity and mortality (see Chapter 22 and 25).

The *risk of increase in disease burden* is also a primary example of the interaction of changes in the physical climate conditions and the vulnerability of people. Recent studies (see Chapter 22) underscore that increasing temperature affects the health of exposed, vulnerable groups due to heat stress (see also section 19.3). The impact of heat stress on an aging populations, such as during the heat wave disaster in 2003 in Europe, illustrates how changing climatic conditions interact with trends in population structure to create key risks.

Globally, the widespread and systemic observed and projected impacts of climate change on biodiversity and ecosystems (see Chapter 4, sections 6.3.1, 6.3.3 and 6.3.4) comprise a key risk in terms of the global loss of provisional, regulating, supporting and cultural ecosystem services. For example, regionally, increasing temperatures in combination with vulnerable aquatic systems and vulnerable aquatic ecosystem services contribute to *a key risk due to the loss of aquatic ecosystems and the services they provide for coastal livelihoods*. Newer studies regarding the degradation of coastal reefs (WRI, 2012) underscore that the degradation levels are particularly high in countries where many people depend on these resources and are also characterized by a high exposure to coastal hazards and a high vulnerability, such as the Philippines and Indonesia.

19.6.2.2. The Role of Adaptation and Alternative Development Pathways

As discussed in section 19.2.4, the identification of key risks depends in part on the underlying socio-economic conditions assumed to occur in the future, which can differ widely across alternative development pathways. This section assesses literature that compares impacts across development pathways, compares the contributions of anthropogenic climate change and socio-economic development (through changes in vulnerability and exposure) to climate-related impacts, and examines the potential for adaptation to reduce those impacts. Based on this assessment, there is *high confidence* both that risks vary substantially across plausible alternative development pathways and that the relative importance of development and climate change varies by sector, region and time period, but in general both are important to understanding possible outcomes. In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a key role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services (Rothman *et al.*, submitted).

Direct comparison of impacts across alternative development pathways shows, for example, that socio-economic conditions are an important determinant of the impacts of climate change on food security, water stress and the consequences of extreme events and sea level rise. The effect of climate change on the number of people at risk from hunger generally spans a range of +/- 10-30 million across the four marker SRES scenarios, each of which assumes different socio-economic futures, but becomes as high as 120-170 million in some analyses based on a scenario (A2) with high population growth (Schmidhuber and Tubiello, 2007). Similarly, the number of people exposed to water stress in a global study is sensitive to population growth assumptions (Arnell and Lloyd-Hughes, Submitted), as are projected water resources in the Middle East under an A1B climate change scenario (Chenoweth

et al., 2012). Assessments of the risks from river flooding depend on alternative future population and land use assumptions (Bouwer *et al.*, 2010; te Linde *et al.*, 2011), and sea level rise impacts depend on development pathways through their effect on the exposure of both the population and economic assets to coastal impacts, as well as on the capacity to invest in protection (Anthoff *et al.*, 2010).

The view that development pathways are an important determinant of risk related to climate change impacts is further supported by two other types of studies: those that examine the vulnerability of subgroups of the current population, and those that compare the relative importance of climate and socio-economic changes to future impacts. The first type finds that variation in current socio-economic conditions explains some of the variation in risks associated with climate and climate change, supporting the idea that alternative development pathways, which describe different patterns of change in these conditions over time, should influence the future risks of climate change. For example, socio-economic conditions have been found to be a key determinant of risks to low-income households due to climate change effects on agriculture (Ahmed *et al.*, 2009; Hertel et al., 2010), to sub-populations due to exposure to heterogeneous regional climate change (Diffenbaugh *et al.*, 2007), and to low-income coastal populations due to storm surges (Dasgupta *et al.*, 2009). Assessments of environmentally induced migration have concluded that migration responses are mediated by a number of social and governance characteristics that can vary widely across societies (Warner, 2010; see 19.4.2.1, 12.4).

The second type of study finds that within a given projection of future climate change and change in socio-economic conditions, typically both are important to determining risks. In fact, the effect of the physical impacts of climate change on globally-aggregated changes in food consumption or risk of hunger have been found to be small relative to changes in these measures driven by socio-economic development alone (Schmidhuber and Tubiello, 2007; Nelson *et al.*, 2010). Similarly, future population growth is found to be an equally (Murray *et al.*, 2012) or more (Fung *et al.*, 2011; Shewe *et al.*, submitted) important determinant of globally-aggregated water stress than the level of climate change, and growth in population and wealth is expected to largely drive potential future damages from tropical cyclones (Bouwer *et al.*, 2007; Pielke Jr., 2007). At the regional level, socio-economic development has also been found to be equally or more important than climate change to impacts in Europe due to sea level rise, through coastal development (Hinkel *et al.*, 2010); heat stress, especially when acclimatization (Watkiss and Hunt, 2012) or aging (Lung *et al.*, In Press) is taken into account; and flood risks, through land use and distributions of buildings and infrastructure (Feyen *et al.*, 2009; Bouwer *et al.*, 2010). Climate change was the dominant driver of flood risks in Europe when future changes in the value of buildings and infrastructure at risk were excluded from the analysis (te Linde *et al.*, 2011; Lung *et al.*, In Press) or when biophysical impacts such as stream discharge, rather than its consequences, were assessed (Ward *et al.*, 2011).

Until recently few studies have addressed the combined impacts of climate change and land use on ecosystems (Warren *et al.*, 2011). Studies of land use change scenarios alone project a large increase in extinction rates in the coming decades (Sala *et al.*, 2000; MEA, 2005), and by the end of the century climate change is generally projected to be an even stronger driver of extinction than is land use change. A study of land bird extinction risk found some sensitivity to four alternative land use scenarios, but by 2100 risk was dominated by the climate change scenario (Sekercioglu, 2008). A study of European land use found that while land use outcomes were more sensitive to the assumed socio-economic scenario, consequences for species depended more on the climate scenario (Berry *et al.*, 2006). Since development often drives land use change, future development that reduces vulnerability in human systems without taking ecosystem preservation into account will often directly reduce ecosystem services, in turn impacting on human systems. Ecosystem based adaptation and development can reduce vulnerability whilst avoiding or minimising ecosystem service loss.

Explicit assessments of the potential for adaptation to reduce risks have indicated that there is substantial scope for reducing impacts of several types, but the capacity to undertake this adaptation is dependent on underlying development pathways. Assessments of the impacts of sea level rise, for example, show that if development pathways allow for substantial investment of resources in adaptation through coastal protection, as opposed to accommodation or abandonment strategies, a substantial reduction in impacts can be an economically rational response for large areas of coastline globally (Nicholls *et al.*, 2008a, 2008b; Anthoff *et al.*, 2010; Nicholls and Cazenave, 2010) and in Europe (Bosello *et al.*, 2012b). For the specific case of sea level rise impacts in Europe, adaptation in the form of increasing dike heights and nourishing beaches was found to reduce the number of people

affected by coastal flooding by a factor of 110 to 228, and total economic damages by a factor of 7 to 9 (Hinkel *et al.*, 2010). In contrast, in some areas with higher current and anticipated future vulnerability such as low-lying island states and parts of Africa and Asia, impacts are expected to be greater and adaptation more difficult (Nicholls *et al.*, 2011).

Similarly, the risk to food security in many regions could be reduced if development pathways increase the capacity for policy and institutional reform, although most impact studies have focused on agricultural production and accounted for adaptation to a limited and varying degree (Lobell *et al.*, 2008; Nelson *et al.*, 2009; Ziervogel and Ericksen, 2010). A study of response options in Sub-Saharan Africa identified substantial scope for adapting to climate change associated with a global warming of 2 °C above pre-industrial levels(Thornton *et al.*, 2011), given substantial investment in institutions, infrastructure, and technology, but was pessimistic about the prospects of adapting to a world with 4 °C of warming (Thornton *et al.*, 2011; see also section 19.6.1). Improved water use efficiency and extension services have been identified as the highest priority agricultural adaptation options available in Europe(Iglesias *et al.*, 2012) and a potentially large role for expanded desalination has been identified for the Middle East (Chenoweth *et al.*, 2012).

19.6.3. Updating Reasons for Concern

The Reasons for Concern (RFCs) are five categories of impacts, or characteristics of impacts, that were introduced in the IPCC TAR(Smith *et al.*, 2001)in order to facilitate interpretation of Article 2 by aggregating a wide range of individual consequences of climate change into a smaller number of broad categories. In AR4, new literature related to the five RFCs was assessed, leading in most cases to confirmation or strengthening of the judgments about their relevance to defining dangerous anthropogenic interference(Schneider *et al.*, 2007; Smith *et al.*, 2009)RFCs are related to the framework of key risks, physical impacts, and vulnerabilities used in this chapter because each RFC is understood to represent a broad category of key risks to society or ecosystems associated with a specific type of physical impact (extreme events, large-scale singular events), system at risk (unique and threatened systems), or characteristic of risk to social-ecological systems (aggregate impacts on those systems, distribution of impacts to those systems). For example, the RFC for extreme events implies a concern for risks to society and ecosystems posed by extreme events, rather than a concern for extreme events *per se*.

In this section we assess new literature related to each of the RFCs, concluding that, compared to judgments presented in AR4 and literature published soon afterward (Smith *et al.*, 2009)levels of risk associated with extreme events, distributional impacts, and large-scale singular events are similar but can be assessed with higher confidence; risks for aggregate damages are similar but confidence in the assessment unchanged, despite the availability of additional studies; and risks to unique and threatened systems are higher above 2°C than assessed previously (see Figure 19-5). We also conclude that because risks depend not only on physical impacts of climate change but also on vulnerabilities of societies and ecosystems to those impacts, RFCs as a reflection of those risks depend on both factors as well (see also 19.1).

19.6.3.1. Variations in RFCs across Socio-Economic Pathways

The determination of key risks as reflected in the Reasons for Concern (RFCs) has not previously been distinguished across alternative development pathways. In the TAR, RFCs took only autonomous adaptation into account(Smith *et al.*, 2001)An update based on literature assessed in AR4 concluded that the RFCs reflect more steeply increasing risk with global average temperature change in each category (Smith *et al.*, 2009; Schneider *et al.*, 2007, AR4 WG2 Chapter 19), but this conclusion was not based on a change in the assessment of future development pathways but rather on evidence of some impacts already becoming apparent, higher likelihoods of some biophysical impacts, and improved identification of currently vulnerable populations.

However, the RFCs represent risks that are determined by both the physical impacts of climate change and the vulnerability of social and ecological systems to climate change stresses. Figure 19-6 illustrates this dependence on vulnerability in a modified version of the burning embers diagram that has been used to characterize risks associated

with RFCs (Smith *et al*., 2001; Smith *et al*., 2009). Current literature is not sufficient to support confident assessment of specific RFCs using this approach; rather, we discuss for each RFC below the degree to which literature supports the general features of such a diagram shown here. In particular, for a given amount of temperature change, risk will be higher for socio-economic conditions producing higher vulnerability and exposure, and lower for futures with lower vulnerability and exposure.

As literature accumulates, it could inform new versions of this figure applied to specific RFCs. For example, studies that employ particular scenarios of socio-economic conditions could be categorized according to the levels of vulnerability represented by those scenarios(van Vuuren *et al*., 2012) to locate results along the horizontal axes, while climate conditions assumed in those studies would locate results along the vertical axis. As with previous versions of the burning embers, however, this new figure does not address issues related to rates of climate change or to when impacts might be realized. The updates of RFCs in 19.6.3.2-19.6.3.6 which follow (and illustrated in Figure 19-5) do not account for differences in vulnerability across development paths; rather, they are based on the same assessment framework as used in AR4 and Smith *et al*. (2009).

[INSERT FIGURE 19-5 HERE
Figure 19-5: The dependence of risk associated with a Reason for Concern (RFC) on the level of climate change, updated from TAR and Smith *et al*. (2009). The color scheme indicates the additional risk due to climate change (with white to purple indicating the lowest to highest level of risk, respectively). The levels of risk illustrated reflect the judgments of Chapter 19 authors. Purple color, introduced here for the first time, reflects the assessment that unique human and natural systems tend to have very limited adaptive capacity (Chapters 4, 24), and hence we have *high confidence* that climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C were exceeded.]

[INSERT FIGURE 19-6 HERE
Figure 19-6: Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and vulnerability of society. This figure is schematic; the degree of risk associated with particular levels of climate change or vulnerability has not been based on a literature assessment, nor associated with a particular RFC. The vulnerability axis is relative rather than absolute: "Medium" vulnerability indicates a future development path in which vulnerability changes over time driven by moderate trends in socio-economic conditions. "Low" and "High" vulnerability indicate futures that are substantially more optimistic or pessimistic, respectively, regarding vulnerability. We assume that judgments made in other burning ember diagrams of the RFCs (Smith *et al*., 2001, 2009) including Figure 19-5, which do not explicitly take changes in vulnerability into account, are consistent with Medium future vulnerability. Arrows and dots illustrate the use of SRES scenario-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socio-economic conditions over time.]

19.6.3.2. Unique and Threatened Systems

Unique and threatened systems include a wide range of physical, biological and human systems that are restricted to relatively narrow geographical ranges and are threatened by future changes in climate (Smith *et al*., 2001). Loss of or damage to such systems are key risks when these systems have great importance to other systems and to society, and because in some cases such loss or damage would be irreversible. AR4 stated with *high confidence* that a warming of up to 2°C above 1990-2000 levels would result in significant impacts on many unique and vulnerable systems, and would increase the endangered status of many threatened species, with increasing adverse impacts (and increasing confidence in this conclusion) at higher temperatures (Schneider *et al*., 2007). Since AR4, there is new and stronger evidence to support this judgment, particularly regarding species and ecosystems, which is now cited in sections 19.6.3.4 and 19.6.3.5 relating to distributional and aggregate impacts of climate change, because the evidence now suggests that climate change impacts on ecosystems is systemic and pervasive, and affects most ecosystems worldwide, not only unique and threatened ecosystems.

Since AR4 there has been increased understanding (see Chapter 4) confirming areas where natural ecosystems are *particularly* vulnerable to climate change and extinctions are *likely* or *very likely* to occur, for example the Wet

Tropics of Queensland, Australia (a World Heritage Area), SW Australia, and the Australian alpine zone (Klausmeyer and Shaw, 2009; Hughes, 2011) where even 1°C of local warming is projected to have negative effects. High extinction risks continue to be identified for the Fynbos and succulent Karoo areas of South Africa for both plants and insects (Midgley and Thuiller, 2011; Kuhlmann *et al.*, 2012; Huntley and Barnard, 2012)Recent research has identified tropical ecosystems, including both tropical wet and dry forests (Deutsch *et al.*, 2009; Wright et al., 2009; Kearney *et al.*, 2009, Toms *et al.*, 2012) and tropical island endemics (Fordham and Brook, 2010) as particularly vulnerable. A study estimated that 600-900 tropical bird species could be committed to extinction if GMT rises by 3.5°C by 2100, mostly in Central America, tropical parts of Mexico and the Andes, and the Brazilian Atlantic forest(Şekercioğlu *et al.*, 2012). For these birds, and for unique ecosystems (e.g. biodiversity hotspots) more generally, extinctions are projected to rapidly increase once global temperatures exceed 2°C above pre-industrial levels(Warren *et al.*, 2011; Şekercioğlu *et al.*, 2012). Since IPCC AR4, there is increasing evidence of the climate risks to polar and mountain regions, including now the Himalayas (Colwell *et al.*, 2008; Shrestha and Aryal, 2011) and to Mediterranean systems(Klausmeyer and Shaw, 2009; Maiorano *et al.*, 2011). Amongst vertebrates, amphibians are still considered the most vulnerable taxon (IPCC AR4, Warren *et al.*, in press.). Coral reef ecosystems are still considered amongst the most vulnerable of unique systems (see section 5.4.1.6), with corals' evolutionary responses to changing conditions being outpaced by climate change (Hoegh-Guldberg, 2012) resulting in projections of extensive reef decline throughout the 21st century, and reef dissolution projected to begin if CO_2 concentrations reach 560 ppm (see section 5.4.1.6). Mangroves continue to be considered particularly at risk, and the combined effect of damage to corals and mangrove threatens unique human communities (see sections 4.3.3, 22.3.3.1).

Regarding physical systems, there is a *high confidence* that an increase in annual mean global surface temperature greater than 2°C above present will eventually lead to a nearly ice-free Arctic Ocean in late summer, and a seasonally ice-free Arctic Ocean within the next 50 years is a very distinct possibility (AR5 WGI Chapter 12; section 19.6.3.6). CMIP5 projections of Arctic sea ice melt project faster loss, more consistent with observations than did the CMIP3 projections used in AR4 (AR5 WGI Chapter 12). Since Arctic sea ice is of critical importance to local peoples and Arctic ecosystems, hence there is a greater threat to the hunting and food sharing culture of the Inuit population and the ecosystems upon which they depend (Crowley, 2011) than was envisaged in AR4.

Similarly, owing to higher projections of sea level rise than in AR4 (AR5 SOD Ch.13), small island states are at greater risk of inundation than previously thought, and a global temperature rise in excess of 1.5°C would fail to protect many islands from inundation (section 24.9.2).

There is new evidence about the risks to human and ecological systems dependent on glacial meltwater. Rapid deglaciation is already occurring (see section 18.5.3). Significant loss of glacial cover in central Asia is possible by the end of the century under the higher climate change scenarios considered by IPCC AR4 (see section 24.9.3). Loss of glacial cover will affect water supplies in arid regions where meltwater contributes significantly to water supplies (Kassel, 2010). Thus projections of glacier melt by mid-century and its hydrological consequences, using an A1B SRES scenario, found projected reductions in meltwater flow from Himalayan glaciers which, if realized, would threaten the food security of 60 million people in the Brahmaputra and Indus basins (Immerzeel *et al.*, 2010) Such threats to water security in parts of Asia(Chakraborty and Newton, 2011; Shrestha *et al.*, 2012) and similar conditions in the foothills of the Andes have implications for tourism, hydropower and agriculture (Chevallier *et al.*, 2011).

This assessment is summarized in the left hand bar in Figure 19-5. Similar to findings of AR4 and Smith *et al.* (2009) but with increased confidence, current literature supports a "yellow" level of risk (moderate risk to some species and systems at recent temperatures), since there are already widespread observed impacts of climate change on unique and threatened systems. A transition to red is located at 1°C, indicating the increasing risk to small islands, coral reefs, the Arctic and unique natural ecosystems as temperature increases. A transition to purple is located around 2°C, to reflect the projected escalating risks referred to above. Unique human and natural systems tend to have very limited adaptive capacity (Chapters 4, 24), and hence we have *high confidence* that climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C were exceeded.

19.6.3.3. Extreme Events

Extreme weather events (e.g., heat waves, intense precipitation, tropical cyclones) trigger impacts that can pose key risks to societies that are exposed and vulnerable. SREX (IPCC, 2012) and the WGI AR5 provide comprehensive assessments indicating overall small changes compared to AR4 in the projected frequency of occurrence, duration, intensity, and extent of extreme events (IPCC, 2012 Chapter 3; AR5 WGI SOD). SREX also clarifies the factors which contribute to vulnerability, and assesses approaches to addressing the latter. The WGI AR5 SOD assesses the physical hazard aspect of risk, stating that, "There has been a strengthening of the evidence for human influence on temperature extremes since AR4 and it is now judged *very likely* that human influence has contributed to the observed changes in temperature extremes since the mid-20th century."(WGI SOD p.10-3). The likelihood of projected 21st century changes in extremes has not changed markedly since AR4 (WGI SOD, Chapters 10,12), but for the first time near term changes (through 2035) are assessed. Among the conclusions are, "It is *very likely* that in the next decades the frequency of warm days and warm nights will increase, while the frequency of cold days and cold nights will decrease at the global scale."(AR5 WGI SOD 11-6) For instance, increases of ~30% occur in the rate of exceedence of daily maximum temperatures above the historical 90th percentile by 2040 (WGI SOD fig. 11-22). WGI also states with respect to temperature extremes that, "This trend will *likely* be visible in an increasing number of regions in the near term" and with regard to precipitation extremes that "in the near term, it is *likely* that the frequency and intensity of heavy precipitation events will increase at the global scale." (WGI SOD, p.11-6). In addition, SREX (Figure SPM 4B) projects a reduction in return period for historical once-in-20-yr precipitation events by about 1/3 by 2046-65. Based on these assessments of the physical hazard alone, we find increased confidence in the AR4 assessment of the risk from extreme events. We also have increased confidence in the AR4 assessment of the risk arising in the near term from the *distribution of impacts* from extreme events because, by their very nature, these events change in a locally and temporally variable fashion with, e.g., a larger change in extreme temperatures at higher latitudes (SREX Figure SPM 4A).

SREX also reviewed literature on the relationship of risk of extreme events to changes in vulnerability and exposure (SREX sections 4.5.4, 4.5.6). For example, growth of megacities both concentrates vulnerability and generates "synchronous failure" which spreads beyond the immediate vicinity of extreme events. Thus increases in local vulnerability and exposure to extreme precipitation can lead to a disproportionate increase in overall risk (SREX sections 4.3.5.1, 9.2.8; Douglas *et al*., 2008; Douglas, 2009; Hallegate *et al*., 2011; Ranger, 2011). Similarly, megacities increase nighttime temperature extremes via the urban heat island effect (SREX section 4.4.5.2) while also enhancing exposure to high air pollution levels (SREX section 9.2.1.2.3). Taken together, evidence supports a worsening of air pollution risk under RCP scenarios in Asian megacities over the next few decades (WGI SOD section 11.3.5.2). This evidence supports a conclusion of disproportionate increase in risk as exposure and vulnerability increase.

Based largely on evidence discussed in AR4, Smith *et al*., (2009) assessed the risk of extreme weather events to increase already at recent temperature and to become large with less than 1°C warming above 1990 temperature, as supported by more recent literature (WGI SOD fig 11-22), which indicates an increase in currently observed 90th-percentile daily maximum temperature exceedences of more than 15% above historical values. Higher confidence expressed in AR5 on attribution of some types of extreme events to human activity, along with the assessment of increased likelihood of temperature and precipitation extremes over the next few decades when GMT (and local temperature) increases are projected to generally remain below 1°C, result in increased confidence in assigning a "yellow" level of risk at recent temperatures in Figure 19-5 and a transition to red beginning below 1°C, consistent with Smith *et al*., (2009). While the additional effect of changes in vulnerability and exposure has not been quantified, based on evidence reviewed in SREX, we judge that modest increases in the social elements of risk would support increasing the level of risk indicated in Figure 19-5 near recent temperatures. The same logic leads us to conclude that decreases in vulnerability and exposure would raise the red-to-yellow transition to higher temperatures.

19.6.3.4. Distribution of Impacts

The potential distribution of impacts is a category of climate change consequences that includes key risks to particular societies and social-ecological systems that may be disproportionately affected due to unequal distribution of vulnerability and of physical climate impacts. AR4 concluded that there is *high confidence* that low-latitude, less-developed areas are generally at greatest risk and found that, because vulnerability to climate change is also highly variable within countries, some population groups in developed countries are also highly vulnerable even to a warming of less than 2°C (Schneider *et al*., 2007). These conclusions remain valid and are now supported by more impact studies that explicitly consider differences in socio-economic conditions across regions or populations that affect vulnerability across regions or populations.

Economic (including insured) disaster losses associated with weather, climate, and geophysical events are higher in developed countries, while fatality rates and economic losses expressed as a proportion of GDP are higher in developing countries (SREX-SPM), a finding that emphasizes the importance of exposure to risk to human systems.

For levels of global temperature rise between 1.5 and 4°C over preindustrial levels, agricultural yields may increase in some regions and decrease in others in ways that may be difficult to compensate for through international trade (Battisti and Naylor, 2009; Penny *et al*., 2010). Areas where there is a significant risk of a decline in regional food security for a global warming of 1.5-2°C(Hare *et al*., 2011) include those surrounding the Namib (Brauch, 2006); the southern half of Russia (Dronin and Kirilenko, 2011); North Africa (Mougou *et al*., 2011, Iglesias *et al*., 2011); the West African Sahel (Ben Mohamed, 2011; Sissoko, 2011), sub-Saharan Africa (Müller *et al*., 2011), South Asia (Lal, 2011), and Bangladesh (Mirza, 2011). Crop yields are expected to decline in Australia (Risbey, 2011; Steffen *et al*., 2011). There are also emerging risks to agriculture generally due to flooding, and of pests and tropospheric ozone (Reilly *et al*., 2007; Avnery *et al*., 2011; Lal, 2011; Sutherst *et al*., 2011; sections 7.3.2.1.2, 7.3.2.2). Whilst particular regions may be more prone to coastal flooding or tropospheric ozone damage, pests and disease may unpredictably affect any region at any time.

The first global scale analysis of climate change's impacts on almost 50,000 species of plants and animals has highlighted that species which are widespread geographically are also at risk (Warren *et al*., in press), not only endemics, which have tended to be the focus of many previous studies, implying a significant and widespread loss of ecosystem services(Gaston and Fuller, 2008; Allesina *et al*., 2009), comprising a new emergent risk (Table 19-3, Entry 2, Chapter 19).

Since AR4, new evidence has emerged highlighting the magnitude of risk of impacts in particular regions, for example in relation to the potential for regional impacts upon ecosystems (see 19.6.3.2), megadeltas, and agricultural systems, which is exacerbated by the potential for changes in the monsoon systems (see 19.6.3.5; WG I SOD 12.5.5.). Hence, overall there is increased evidence that low-latitude and less-developed areas generally face greater risk than higher-latitude and more-developed countries (Smith *et al*., 2009). At the same time it has been found that developed countries have less resilience to, for example, recently experienced extreme weather events than previously thought, creating more localised issues of differential vulnerability in particular areas of the developed world. For this reason, and since climate change impacts are already beginning to emerge in observations (see Chapter 2), the transition from white to yellow levels of risk in Figure 19-5 is now assessed to occur at recent temperatures, and the transition from red to yellow is between 1 and 2°C, both as indicated in Smith *et al*., (2009).

19.6.3.5. Aggregate Impacts

The RFC pertaining to aggregate impacts includes risks to society or ecosystems that are aggregated globally into a single metric, such as monetary damages, lives affected, or lives lost, although most aggregations in the literature are carried out in monetary terms. Estimates of the aggregate, economy-wide risks of climate change since AR4 continue to exhibit a *low level of agreement*. Studies at the sectoral level have been refined with new data and models, and have assessed new sectors.

For example, impacts on the health sector have not previously included the direct effects of heat and humidity on productivity. New studies indicate that there is *high confidence* that these effects will have a negative impact on global economic output and human welfare (see 10.9.2.1). Heat- and humidity-related declines in available workdays of up to 19% by the middle of the century have been projected in some regions (Kjellstrom et al., 2009; SRES A2 scenario). When considering effects of disease as well, labor productivity losses are projected to lead to a global output loss of ~1.8% with ~3°C of global average warming above pre-Industrial levels and ~4.6% with ~6°C of warming (Roson and Mensbrugghe, 2012).

AR4 stated with medium confidence that approximately 20-30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above pre-industrial levels (Fischlin *et al*., 2007). Since AR4 the literature has expanded in many ways with respect to climate change impacts on biodiversity. Firstly, new literature has added to the evidence of increased extinction risk, for example to species in unique and threatened systems (see 19.6.3.2) and in tropical, polar and mountain ecosystems (see 19.6.3.2). Secondly there are many more detailed studies quantifying extinction risks, of which several include also studies on possible adaptive measures to support conservation (e.g. Hunter *et al*., 2010; Amstrup *et al*., 2010; Pearman *et al*., 2011; Lenoir *et al*., 2008; Balint *et al*., 2011; Barnosky *et al*., 2012; Ledit *et al*., 2012; Norberg *et al*., 2012; Bellard *et al*., 2012). More studies have scrutinized previously known caveats and tried to asses their role in either under- or overestimating notably extinction risks (e.g. Beale et al., 2008; Cressey, 2008; Randin *et al*., 2009; He and Hubbell, 2011; Harte and Kitzes, 2012), including the role of evolution (Norberg *et al*., 2012), while others have stressed the relevance of past climate change insights for this issue (e.g. Barnosky *et al*., 2012) with varying success (e.g. Botkin *et al*., 2009; Willis and Bhagwat, 2009; Willis *et al*., 2010). Overall, the AR4 statement relating to extinction risk still stands.

There is increased evidence of observed climate change impacts (including those arising from changes in climate variability) on ecosystems, including range loss in plants and animals and changes in phenology(Gange *et al*., 2007; Foden *et al*., 2007; Pudas *et al*., 2008; Devictor *et al*., 2008; Kusano and Inoue, 2008; Beckage *et al*., 2008; Thibault and Brown, 2008; Kelly and Goulden, 2008; Moreno-Rueda *et al*., 2009; Furgal and Prowse, 2009), and on ecosystem composition and function (Blaum *et al*., 2007; le Roux and McGeoch, 2008; Vittoz *et al*., 2009; de Sassi and Tylianakis, 2012; Table 19-3, Entry 2, Chapter 19). Much new work has focused on synergistic impacts of climate-change induced increases in fire, drought, disease, and pests (Flannigan *et al*., 2009; Krawchuk *et al*., 2009; Hegland *et al*., 2009; Koeller *et al*., 2009). All this evidence accrues to a projection of more severe aggregate impacts of climate change on ecosystems and their services globally than in AR4.

New work has demonstrated that the expected large turnovers of up to 60% in marine species assemblages in response to unmitigated (SRES A1B) climate change by the 2050s, combined with shrinkage of fish body weight of 14–24% (Cheung *et al*., 2009; Cheung *et al*., 2012) put marine ecosystem functioning at risk with negative consequences for fishing industries, coastal communities and wildlife that are dependent on marine resources(Lam *et al*., 2012).

Assessments of risks to coastal populations due to sea level rise have advanced through the application of more geographically detailed coastal databases in models that include adaptation options (Hinkel and Klein, 2009). One global study found that without investment in coastal protection, under the SRES A1B population scenario 50 cm of globally uniform sea level rise would displace about 72 million people by 2100, while 2 m of globally uniform sea level rise would displace about 187 million people. The incremental annual costs of protection are estimated at $25 billion/year and $270 billion/year [in 1995 USD], respectively (Nicholls et al., 2011; A1B scenario). Similarly, an assessment of risks from tropical cyclones projected a doubling of cyclone damages globally due to climate change alone, (0.01% of global GDP), and a further doubling due to expected increases in GDP and related exposure, on top of present day baseline damages of $26 billion/yr (Mendelsohn et al., 2012; A1B scenario).

Assessments of economy-wide consequences of climate change report results either as total damages or as marginal damages, the latter represented by the social cost of carbon (SCC). Estimates of global aggregate impacts from integrated assessment models (Figure 19-7) exhibit *a low level of agreement* (Ackerman et al., 2011; Anthoff and Tol, 2010b; Bosello et al., 2012; Hope, 2013a, 2013b; Nordhaus, 2008, 2010; Roson and Mensbrugghe, 2012; Waldhoff et al., 2013). Sectoral breakdowns also exhibit *a low level of agreement* (Figure 19-8) (Anthoff and Tol,

2010b; Anthoff et al., 2013; Nordhaus, 2007, 2008; Roson and Mensbrugghe, 2012). There is *very high confidence* that aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries and populations. For this reason, as well as the existence of only a few studies with sectoral detail that employ alternative development pathways, it is difficult to detect a monotonic relationship between vulnerability and aggregate risks at the global scale. In some locations and amongst some groups of people with high exposure and high vulnerability, net costs per capita will be significantly larger than the global average (Anthoff *et al*., 2009; Nordhaus, 2011; Warren, 2011).

[INSERT FIGURE 19-7 HERE
Figure 19-7: Representative global damage estimates, shown as a percentage loss of global output as a function of temperature, from integrated assessment models employing their own reference scenarios. PAGE 2009: (Hope, 2013a, 2013b). FUND 3.8: (Anthoff and Tol, 2010b; Anthoff *et al*., 2013; Waldhoff *et al*., 2013). RICE 2010: (Nordhaus, 2010). CRED: (Ackerman et al., 2011). ENVISAGE: (Roson and Mensbrugghe, 2012). GECON: (Nordhaus, 2006). ICES: (Bosello *et al*., 2012a). For PAGE 2009 and FUND 3.8, the shaded region indicates the range spanned by the 5th and 95th percentile of outputs in Monte Carlo mode. For CRED 1.3, the shaded region indicates the range spanned by four alternative damage functions. In CRED at 6°C, mean damages are 32% of GDP and the largest of the four damage functions yields 50% loss of GDP.]

[INSERT FIGURE 19-8 HERE
Figure 19-8: Breakdown of damages at 2.5°C above pre-industrial by sector in the DICE 2007 calibration (Nordhaus, 2007; Nordhaus, 2008), FUND 3.8 (Anthoff and Tol, 2010b; Anthoff *et al*., 2013; Waldhoff *et al*., 2013) modal damages and ENVISAGE (Roson and Mensbrugghe, 2012), reflecting a *low level of agreement* among the integrated assessment models used to estimate global aggregate damages. Note that the DICE calibration does not include damages due to changes in water resources as distinct from temperature impacts on agriculture and forestry, and FUND and ENVISAGE do not include expected catastrophic damages. Representations of changes in energy demand, coastal/sea level impacts, health and labor productivity impacts, and impacts on settlements, ecosystem and tourism are included in all three models. Grey lines span the 5th to 95th percentile of estimates from FUND. The 95th percentile of energy sector damages in FUND is 2.2% of GDP.]

Uncertainty in estimates of global aggregate impacts is further increased because most IAMs exclude a number of potentially significant factors(Yohe, 2008; Füssel, 2010; Kopp *et al*., 2012), including the consequences of earth system tipping points (Kopp and Mignone, 2012; Lenton and Ciscar, 2013), intersectoral and interregional interactions (see section 19.3) (Bosello *et al*., 2012; Warren, 2011), and imperfectly substitutable environmental goods, which reflect the fact that impacts on (for example) ecosystems cannot be replaced 1-for-1 by an increased consumption of material goods (Kopp *et al*., 2012; Sterner and Persson, 2008; Weitzman, 2010). Additionally, studies lack evidence for extrapolating damages from temperature increases at which impact studies have been carried out to higher temperatures (Ackerman and Stanton, 2012; Ackerman *et al*., 2010; Kopp *et al*., 2012; Weitzman, 2010). There is *high confidence* that the exclusion of these factors together lead to an underestimate of global aggregate impacts. In addition, adaptation is treated differently across modeling studies (Bosello *et al*., 2010; de Bruin *et al*., 2009; Füssel, 2010; Hope, 2006; Patt *et al*., 2010) and affects aggregate damage estimates in ambiguous ways.

Alternative measures of global aggregate damages have been proposed based upon historical and geographic relationships between temperature and economic growth. *Limited evidence* suggests that higher temperatures decrease economic growth rates in low-income countries by ~1.3%-2.5%/year per 1°C (Dell et al., 2009, 2012; Hsiang, 2010) (see 10.9.2.1 and 18.4.2.1). Consistent with studies on the relationship between temperature and labor productivity, higher temperatures appear to reduce both agricultural and industrial output in low-income countries; they also appear to increase political instability, which will also contribute to decreased economic growth (Dell *et al*., 2012). Modest changes in economic growth rate can accumulate to large changes in output over time, although the studies conducted to date do not address the possibility of long-term adaptation.

The social cost of carbon (SCC) is an alternative index of aggregate damages that monetizes the expected welfare impacts of a marginal increase in carbon dioxide emissions in a given year (i.e., the welfare loss associated with an additional tonne of CO_2 emitted), aggregated across space, time, and probability (e.g., Newbold *et al*., 2010;

Nordhaus, 2011a; Tol, 2011; Kopp and Mignone, 2012). As of AR4, a survey of 103 estimates of the SCC from 28 published studies found a mean of $25/tonne CO_2 and a 95th percentile value of $95/tonne CO_2 (Tol, 2005). Numerical estimates of the SCC published since AR4 continue to span a large range. Peer-reviewed estimates (as compiled by Tol, 2011, 2013, with the addition of estimates from Kopp *et al.* 2012) range from -$2 to $1000/tonne CO_2, with most estimates between $4 and $50/tonne CO_2 (in inflation-adjusted 2010 dollars, for CO_2 emissions occuring in the first fifteen years of the twenty-first century) (Ackerman and Munitz, 2012; Ackerman and Stanton, 2012; Anthoff and Tol, 2010a; Anthoff *et al.*, 2009a, 2009b, 2009c; Cai et al., 2012; Hope, 2008a, 2013b, 2008b; Kopp et al., 2012; Marten and Newbold, 2012; Narita *et al.*, 2009, 2010; Newbold *et al.*, 2010; Nordhaus, 2008, 2010; Stern and Taylor, 2007; Tol, 2011, 2012, 2013).

Uncertainty in SCC estimates is high due to the uncertainty in underlying total damage estimates, under-representation of uncertainty in socio-economic scenarios, under-representation in some models of uncertainty in climate/carbon cycle, fidelity issues regarding the reduced-form climate/carbon cycle models used in the principal IAMs (Hof *et al.*, 2011; Marten, 2011; van Vuuren et al., 2011; Warren *et al.*, 2010), and low level of agreement regarding the appropriate framework for aggregating impacts over time (discounting), regions (equity weighing), and states of the world (risk aversion). Quantitative analyses have shown that SCC estimates can vary by at least ~2x depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, United States Government, 2010), at least ~3x due to the incorporation of uncertainty (Kopp *et al.*, 2012, p.2012), and at least ~4x due to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012). A further source of uncertainty is whether and how the possibility of catastrophic damages is accounted for (Dietz, 2010; Nordhaus, 2011b; Weitzman, 2009), which requires bounding potential losses with a parameter akin to the value of a statistical life (representing, essentially, willingness to pay to avoid human extinction) (Dietz, 2010; Kopp *et al.*, 2012, p.2012). Without such a parameter, SCC estimates incorporating risk aversion and potential catastrophic impacts can be unboundedly high.

Thus the risk for aggregate damages is similar to that expressed in AR4 and Smith *et al.*, (2009) as indicated in Figure 19-5, with confidence in the assessment unchanged.

19.6.3.6. Large-Scale Singular Events: Physical, Ecological, and Social System Thresholds and Irreversible Change

Large-scale singular events (sometimes called “tipping points”) are abrupt and drastic changes in physical, ecological, or social systems in response to smooth variations in driving forces (Smith *et al.*, 2001; Smith *et al.,* 2009). Combined with widespread vulnerability and exposure, they pose key risks because of the potential magnitude of the consequences, the rate at which they would occur, and the limited ability of society to cope with them.

Regarding singular events in physical systems, AR4 expressed *medium confidence* that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic Ice Sheet (WAIS), would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4°C (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 m or more (Schneider *et al.*, 2007). Recent studies are consistent with these judgments but provide a more nuanced view (see WGI SOD Chapter. 13). At the current time, the Greenland ice sheet is making about twice the contribution to sea level rise as the Antarctic ice sheet (Shepherd *et al.*, 2013). Recent studies (Kopp *et al.* 2009; McKay *et al.*, 2011; Dutton and Lambeck 2012) suggest a comparable contribution from the two ice sheets during the Last Interglacial, which provides a partial analog for 21st century warming. One study (Robinson *et al.*, 2012) lowered the threshold for near-complete melting of the Greenland ice sheet to 0.8-3.2°C above preindustrial temperatures from 1.9-5.1°C global warming in AR4. Expert elicitations (Kriegler *et al.*, 2009) and other approaches (Good *et al.*, 2011) have led to assessments that a complete melting of Greenland is *unlikely* below 2°C and *likely* above 4°C compared to recent temperatures. The question of whether the melting of Greenland is irreversible, once a significant fraction of ice has been lost remains contested(Lunt *et al.*, 2004; Ridley *et al.*, 2010; Robinson *et al.*, 2012). AR5 notes that a significant decay of the ice sheet may be irreversible (AR5 WGI SOD SPM-17). A threshold for the disintegration of WAIS remains difficult to identify due to shortcomings in modeling the dynamical component of ice loss. Extreme exposure and vulnerability to the

magnitude of sea level rise associated with loss of a significant fraction of either ice sheet is found worldwide (Nicholls and Tol, 2006).

There is also additional evidence regarding singular events in other physical systems. Feedback processes in the Earth system cause accelerated emissions of methane from wetlands, terrestrial permafrost and ocean hydrates but temperature sensitivity of these processes is not known and progress in determining this has been slow. However, the risk of a substantial carbon release from these processes increases with warming. Model results indicate additional cumulative methane emissions due to these sources potentially becoming comparable to cumulative direct anthropogenic emissions on a century timescale but no sudden, large release short of millennial timescales (AR5 WGI SOD 6.4, Figure 6.37; O'Connor *et al*., 2010, Archer *et al*., 2009, Zhang *et al*., 2009).

AR4 stated that Arctic summer sea ice disappears almost entirely in some projections by the end of the century (AR4 WGI 10.3); AR5 finds there is also a *high confidence* that an increase in annual mean global surface temperature greater than 2°C above present will eventually lead to a nearly ice-free Arctic Ocean in late summer. A seasonally ice-free Arctic Ocean within the next 50 years is a very distinct possibility, even though later dates cannot be excluded (AR5 WGI 12-5). Whether or not the physical process is reversible, effects of ice loss on biodiversity may not be.

Large uncertainties remain in estimating the probability of a shutdown of the Atlantic meridional circulation. One expert elicitation finds the chance of a shutdown to be between 0 and 60% for global average warming between 2-4°C, and between 5 and 95% for 4-8°C of warming relative to 2000(Kriegler *et al*., 2009). AR5 assesses a collapse of the AMOC during this century as *very unlikely*, and *unlikely* that a collapse would occur in succeeding centuries under scenarios considered (AR5WGI SOD SPM-15).

Recent observational evidence confirms the susceptibility of the Amazon to drought and fire (Adams *et al*., 2009), and recent improvements to models provide increased confidence in the existence of a tipping point in the Amazon from forest to grassland as the dominant ecosystem (Jones *et al*., 2009; Lapola *et al*., 2009; Malhi *et al*., 2009). One recent study suggests that the Amazon may be less susceptible to crossing a tipping point than previously thought (Cox *et al*., 2013), although this is contingent upon the role of CO_2 fertilisation being as strong as models project.

Risks to biological systems include species extinction (see 19.6.3.2), and regime shifts, which are sometimes classified as large-scale singular events. Such tipping points will occur in different ecosystems with different levels of warming (Warren *et al*., 2010). Although there is still uncertainty over when such points might be crossed, a significant increase in extinction rates is considered *likely* for GMT rise of more than 2°C above pre-industrial levels.

Based on the weight of the above evidence, we judge that the risk from large-scale singular events remains comparable to that assessed in AR4, as indicated by Smith *et al*. (2009) and Figure 19-5.

19.7. Assessment of Response Strategies to Manage Risks

The management of key and emerging risks of climate change can include mitigation that reduces the likelihood of climate changes and physical impacts and adaptation that reduces the vulnerability of society and ecosystems to both. Key risks, impacts, and vulnerabilities to which societies and ecosystems may be subject will depend in large part on the mix of mitigation and adaptation measures undertaken, as will the nature of Reasons for Concern (19.6). This section therefore assesses relationships between mitigation, adaptation, and the residual impacts that generate key and emerging risks. It also considers limits to both mitigation and adaptation responses, because understanding where these limits lie is critical to anticipating risks that may be unavoidable. Potential impacts involving thresholds for large changes in physical, ecological, and social systems (19.6.3.6) are particularly important elements of key risks, and the section therefore assesses response strategies aimed at avoiding or adapting to them.

19.7.1. Relationship between Adaptation Efforts, Mitigation Efforts, and Residual Impacts

Evaluating the potential mixes of mitigation, adaptation, and impacts is made complicated by the fact that it requires joint consideration of alternative outcomes for both climate change and socio-economic development. Such an approach is further complicated because socio-economic development pathways will influence future emissions, land use change, and therefore climate change (WGIII, Chapter 5), and in turn climate change will influence development pathways through feedbacks on social and economic systems, including policy responses (AR5 WGII Chapter 2, Chapter 20).

One perspective on these relationships is provided by studies of the benefits of mitigation, i.e., the impacts avoided by mitigation, which sometimes also account for adaptation. Avoided impacts vary significantly across regions due to (a) differing levels of regional (as opposed to global) climate change, (b) differing numbers of people and levels of resources at risk in different regions (e.g. presence of unique ecosystems or the size of the human population exposed to impacts), and (c) differing sensitivities and adaptive capacities of humans, species or ecosystems in different regions. Similarly, residual impacts will differ between sectors due to (a) different levels of sensitivity and (b) differing levels of adaptive capacity. They will also differ over time depending on which aspect of the physical climate system is driving them. Benefits accrue most rapidly for impacts associated with ocean acidification, less rapidly for those associated with change in temperature and/or precipitation, and least rapidly for impacts associated with sea level rise such as coastal flooding, loss of mangroves and coastal wetlands (AR5 WGI SOD Figure 6.41). Sea level rise responds very slowly to mitigation efforts so that mitigation can reduce the rate of sea level rise but under most emissions scenarios, cannot halt it altogether (Meehl *et al*., 2012). Global temperature can be stabilized as a result of mitigation efforts, but even if anthropogenic CO_2 emissions were reduced to zero, global average temperature would not decline significantly from its peak over a century timescale (Matthews and Caldeira, 2008; Solomon *et al*., 2010). Ocean acidification responds more quickly to changes in emissions of CO_2 than does global temperature, with the rise in pH ceasing several decades after stringent emission reductions begin (Bernie *et al*., 2010).

Figure 19-9 gives an example of sectoral variation within three global analyses of the avoided impacts of climate change resulting from efforts to implement stringent mitigation (Arnell *et al*., 2013; Warren *et al*., in press; Warren *et al*., submitted). The figure shows the impacts avoided by reducing greenhouse gas emissions from either SRES A1B or SRES A1FI scenario, to one in which global greenhouse gas emissions peak in 2016 and are reduced thereafter at 5% annually, constraining global mean temperature rise to 2ºC above pre-industrial levels. In all three studies, global temperatures are simulated to reach between 4º and 5.6ºC above pre-industrial by 2100, consistent with WGI AR4, whilst under the pathways peaking in 2016 it reaches just above 2ºC. Global average sea level rises by 47-55cm by 2100 in the scenarios with no mitigation, with the increase reduced to 30 cm by the most aggressive mitigation pathway. Overall, the impacts avoided increase over time and by the end of the century range from 20-70% below SRES A1B base case impacts, or 30-80% below SRES A1FI base case impacts, across sectors (Figure 19-9). Specifically Arnell (2013) identified large benefits for crop productivity, exposure to coastal and fluvial flooding, and energy use for cooling, where impacts avoided relative to an A1FI baseline ranged from 60 to 80% by 2100 (Figure 19-9), whilst avoided impacts were smaller for water availability (20%). Similarly Warren *et al*. (2012) found that 60% of the impacts on biodiversity, in terms of projected loss in species range in 2100, can be avoided if warming can be limited to 2 degrees above pre-industrial levels (Figure 19-9). The proportion of impacts avoided *at the global scale* was relatively robust for most indicators across different climate model patterns, but the absolute magnitude of avoided impacts varied considerably.

[INSERT FIGURE 19-9 HERE
Figure 19-9: Climate change impacts avoided by a mitigation scenario compared to two no-mitigation cases (SRES A1B and A1FI scenarios), showing the uncertainty due to regional climate change impacts projection with 7 GCMs. Since increases and decreases in water stress, flood risks and crop suitability are not co-located and affect different regions, these effects are not combined. From Arnell *et al*., 2013, Warren *et al*., in press, Warren *et al*., submitted.]

All three studies (Arnell *et al*. 2013; Warren *et al*., in press*;* Warren *et al*., submitted), which considered emission reduction rates of between 2 and 5% annually, showed that fewer impacts can be avoided when global emissions do not peak until 2030, even if emissions are reduced at 5% thereafter, than if emissions peak in 2016 and are reduced

at 2% annually thereafter. A complementary economic analysis with the PAGE integrated assessment model showed that if global emissions peak in 2016, around one half of the economic impacts that would otherwise accrue by 2100 can be avoided, but if mitigation is delayed so that emissions peak in 2030, only around a third of the impacts can be avoided regardless of whether equity weightings are used in the economic model (Warren *et al*., submitted).

The above finding of the importance of an early peaking date for global emissions in avoiding climate change impacts, is consistent with an underlying independent finding that the later global emissions peak, the faster emissions must subsequently be reduced to obtain the same probability of meeting a given constraint on global temperature rise (Kalbekken and Rive, 2007; Vaughan *et al*., 2009; Huntingford *et al*., 2012). Example findings from these three studies are that (i) a 20 year delay in reducing emissions leads to a requirement of a 5-11 times greater emissions reduction to stay below identical levels of warming (ii) delaying the peaking date of global emissions from 2015 to 2025 leads to a requirement of more than doubling the post-peak emission reduction rate to maintain a 50% probability of constraining global temperature rise to 2°C above pre-industrial levels. The common finding of a tradeoff between emission reduction rate and the date at which global emission peak reflects the relatively fixed relationship between total cumulative CO_2 emissions and peak temperature change (WG1, Chapter 12).

Other studies have also quantified the benefits of mitigation. Taking the socioeconomic trends in the A2 scenario and exploring futures with and without climate change policy shows that mitigation can reduce by 80-95% the people additionally at risk of hunger in 2080 in the SRES A2 scenario (mostly in Africa), corresponding to a global saving of an estimated 23-34 billion US$ in terms of agricultural output (Tubiello and Fischer, 2007). Benefits varied regionally and were negative in some cases, for example in developed countries due to a positive, though uncertain, effect of CO_2 fertilisation. Similarly, mitigation was found to reduce overall potential welfare losses in the EU from 0.4-1% to 0.2-0.3%(Ciscar *et al*., 2011) with losses in the agricultural sector changing to gains, and the numbers of additional people affected by fluvial flooding decreasing from 318-396,000 annually to 251-276,000 annually. Fung *et al*. (2011) and Arnell *et al*. (2009) both found that projected climate change induced increases in water stress globally for a global temperature rise of 4°C above pre-industrial levels would be halved were global temperature rise to be constrained to 2°C.

Overall this suggests that early, stringent mitigation can avoid a large proportion of the impacts of climate change that would otherwise occur during the second half of the 21st century, irrespective of whether impacts are measured in physical or economic terms. Studies showed that because mitigation reduces the rate of temperature increase, stringent mitigation could increase by 3 to 4 decades the time available for adaptation to a particular level of global temperature rise and thus impacts (Arnell *et al*. 2013, Warren *et al*., in press). A limitation of all these studies, is the uneven treatment of adaptation, which has been explored thoroughly in the context of sea level rise (Nicholls *et al*., 2011) but less well in other contexts.

Mitigation scenarios in category 1 tend to constrain global temperature rise to between A and B degrees C above pre-industrial, significantly reducing the likelihood of occurrence of the following climate change impacts (list tbc) and the breaching of the following tipping points in the earth system (list tbc). Scenarios in category 2 on the other hand constrain global temperature rise to between C and D, also reducing these outcomes, but to a less significant extent. Scenarios in categories 4 to 6 are projected to result in temperature rise of above 4°C and would allow significant risks to persist in all the key areas listed in Table 19-3. Scenarios in category 3 produce modest reductions in the risks (Figure 19-10).

[INSERT FIGURE 19-10 HERE
Figure 19-10 (forthcoming): relates the categories of mitigation scenario considered in AR5 WGIII, to global temperature outcomes (consistent with the WGI calculations; data taken from Chapter 6 - WGIII). It also relates these temperature outcomes to some salient projected climate change impacts for the different levels of global temperature rise, focusing on those impacts which are less affected by the socioeconomic development pathway.]

19.7.2. Limits to Mitigation

Mitigation possibilities are not unlimited. Assessment of maximum feasible mitigation (and lowest feasible emissions pathways) must account for the fact that feasibility is a subjective concept encompassing technological, economic, political, and social dimensions (Hare *et al.,* 2010, UNEP Chapter 2). Most mitigation studies have focused on technical feasibility, for example demonstrating that it is possible to reduce emissions enough to have at least a 50% chance of limiting warming to less than 2 °C relative to pre-industrial (den Elzen and van Vuuren, 2007; Clarke *et al*., 2009; Edenhofer *et al*., 2010; Hare *et al*., 2010; O'Neill *et al*., 2010). Such scenarios lead to pathways in which global emissions peak within the next 1-2 decades and decline to 50-80% below 1990 levels by 2050, and in some cases exhibit negative emissions before the end of the century. In contrast, no integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5 °C with at least 50% likelihood (UNEP, 2010; Ranger et al., 2012). The highest emission reduction rates considered in most integrated modeling studies that attempt to minimize mitigation cost is typically between 3 and 4% but with larger values not ruled out (den Elzen et al. 2010), whilst other studies highlight that for an additional cost higher rates may be achievable (Climate Change Committee, 2008, O'Neill *et al.,* 2010).

However, most studies of feasibility include a number of idealized assumptions, including availability of a wide range of mitigation technologies such as large-scale renewable energy, carbon capture and storage, and large-scale biomass energy. Most also assume universal participation in mitigation efforts beginning immediately, economically optimal reductions (i.e., reductions are made wherever they are cheapest), and no constraints on policy implementation. Any deviation from these idealized assumptions can significantly limit feasible mitigation reductions(Knopf *et al*., 2010; Rogelj *et al*., 2012). For example, delayed participation in reductions by non-OECD countries made concentration limits such as 450 ppm CO_2eq (roughly consistent with a 50% chance of remaining below 2 °C relative to pre-industrial), and in some cases even 550 ppm CO_2eq, unachievable in some models unless temporary overshoot of these targets were allowed(Clarke *et al*., 2009) but not in others (Waldhoff and Fawcett, 2011). Technology limits, such as unavailability of CCS or limited expansion of renewables or biomass makes stabilization at 450 ppm CO_2eq (or 2 °C with a 50% chance) unachievable in some models (Krey and Riahi, 2009; van Vliet *et al*., 2012). Costs may also become unacceptably high; for example, if low carbon power plants and other infrastructure were limited to new installations (as opposed to replacement of existing stock), the maximum emissions reduction rate would be limited to about 3%/yr (Davis *et al*., 2010). Similarly, if the political will to implement coordinated mitigation policies within or across a large number of countries is limited, peak emissions and subsequent reductions would be delayed (Webster, 2010).

These considerations have led some analysts to doubt the plausibility of limiting warming to 2 °C (Anderson and Bows, 2008; Tol, 2009; Anderson and Bows, 2011). "Emergency mitigation" options have also been considered that would go beyond the measures considered in most mitigation analyses (van Vuuren and Stehfest, 2009; Swart and Marinova, 2010). These include drastic emissions reductions achieved through limits on energy consumption (Anderson and Bows, 2011) or geoengineering through management of the earth's radiation budget (19.5.4; WGI Chapters 6, 7).

19.7.3. Avoiding Thresholds, Irreversible Change, and Large-Scale Singularities in the Earth System

Section 19.6.3 highlighted the reasons for concern related to non-linear changes in the Earth system, whereby anthropogenic forcings might cause irreversible and potentially rapid transitions. The risk of triggering these transitions generally increases with increasing anthropogenic climate forcings / climate change (Lenton *et al*., 2008; Kriegler *et al*., 2009; Levermann *et al*., 2011). Reducing greenhouse gas emissions is projected to reduce the risks of triggering such transitions. Adaptation (see 19.7.2.2) could reduce their potential consequences, but the efficacy of adaptation might be limited, for example for rapid transitions.

Several studies have sought to identify levels of atmospheric greenhouse gas concentrations or global average temperature change that would limit the risks of triggering these transitions (e.g., Keller *et al*., 2008; Kriegler *et al*., 2009; Lenton *et al*., 2008). It is important to distinguish between triggering and experiencing a threshold response

because model simulations suggest that there can be sizeable delays between the two (e.g., Lenton et al., 2008). A risk assessment based on expert elicitation (Lenton *et al*., 2008) finds that limiting global mean temperature increase to approximately 3°C above present values would considerably reduce the risks of triggering examples of potential climate threshold responses such as an Amazon rainforest dieback, a melting of the West Antarctic ice sheet (WAIS), a collapse of the thermohaline circulation / Atlantic meridional overturning circulation (THC/AMOC; see also 19.6.3.6), and disruptions of the Sahara/Sahel and West African monsoon and the El Niño-Southern Oscillation systems. Staying below this 3°C temperature limit does not entirely eliminate the risks of triggering these events (Hansen *et al*., 2008; Kriegler *et al*., 2009; Levermann *et al*., 2012; Zickfeld *et al*., 2010). In addition, this 3 ºC limit could still result in considerable risks of triggering threshold responses such as a disintegration of the Greenland Ice Sheet or a melting of the Arctic summer sea-ice (See 19.6.3.6; Lenton *et al*., 2008; Levermann *et al*., 2012). Past anthropogenic climate forcings may have already triggered some climate threshold responses (Lenton et al., 2008; Urban and Keller, 2010). In particular, evidence from the Last Interglacial suggests that 2°C may be a more appropriate indicator of high risk for a WAIS disintegration (Kopp *et al*., 2009; McKay *et al.,* 2011), a temperature limit that may be difficult to achieve with high probability (see section 19.7.2.1). In general, there is *low confidence* in the location of such temperature limits due to disagreements among experts. Estimates of such temperature limits can change over time (Oppenheimer et al., 2008) and may be subject to overconfidence that can introduce a downward bias in risk estimates of low-probability events (Morgan and Henrion, 1995). The climate threshold responses can interact (e.g., Kriegler *et al*., 2009). Other climate change metrics (e.g., rates of changes or atmospheric carbon dioxide concentrations) can also be important in the consideration of response strategies (Lenton, 2011a; McAlpine *et al*., 2010; Steffen *et al*., 2011).

Several analyses have performed risk- and decision-analyses for specific thresholds, mostly focusing on a persistent weakening or collapse of the THC/MOC (Bahn *et al*., 2011; McInerney *et al*., 2012; Urban and Keller, 2010; Zickfeld and Bruckner, 2008). Experiencing a THC/MOC collapse has been assessed as *very unlikely* in this century and *unlikely* in subsequent centuries under scenarios considered in AR5 (AR5 WGI SOD SPM-15). However, due to the long response time of the THC/MOC, the probability of triggering an eventual collapse within a certain time period can be substantially higher than the probability of experiencing it (Urban and Keller, 2010). A probabilistic analysis sampling a subset of the relevant uncertainties concluded that reducing the probability of a collapse within the next few centuries to one in ten requires emissions reductions of roughly 60% relative to a business-as-usual strategy by 2050 (McInerney and Keller, 2008). Bruckner and Zickfeld (2009) show that, under their worst-case assumptions about key parameter values emissions mitigation would need to begin within the next two decades to avoid reducing the overturning rate by more than 50%. Threshold risk estimates and risk-management strategies are sensitive to factors such as the representation of the uncertainties and the decision-making frameworks (McInerney *et al*., 2012; Polasky *et al*., 2011). Other analyses have examined how the consideration of threshold events affects response strategies. For example, the design of risk-management strategies could be informed by observation and projection systems that would provide an actionable early warning signal of an approaching threshold response. Learning about key uncertain parameters (e.g., climate sensitivity or impacts of a threshold response) can considerably affect risk-management strategies and have a sizeable economic value of information (Keller *et al*., 2004; Lorenz *et al*., 2012). However, there is *low confidence* in the feasibility and requirements for such systems due to the limited number of studies and their focus on highly simplified situations (Keller and McInerney, 2008; Lenton, 2011b, Lorenz *et al*., 2012). In some decision-analytic frameworks, knowing that a threshold has been crossed can lead to reductions in emissions mitigation and a shift of resources toward adaptation and/or geoengineering (Guillerminet and Tol, 2008; Keller *et al*., 2004; Lenton, 2011b; Swart and Marinova, 2010).

19.7.4. Avoiding Tipping Points in Social/Ecological Systems

Tipping points (see Glossary) in socio-ecological systems are defined as thresholds beyond which impacts increase non-linearly to the detriment of both human and natural systems. They pose a particularly important risk because they can be initiated rapidly without warning, inducing a need for rapid response from human systems. Because human and ecological systems are linked by the services that ecosystems provide to society (Lubchenko and Petes, 2010; McLeod and Leslie 2009), tipping points may be crossed when either the ecosystem services are disrupted and/or the social/economic networks are disrupted (Renaud *et al*., 2010). Climate change provides a stress on these services and networks that increases the potential for tipping points to be crossed, although they may be crossed due

to other types of stresses even in the absence of climate change. For example, in dryland ecosystems, overgrazing has caused grassland-to-desert transitions in a number of locations (Pimm, 2009).

The crossing of tipping points due to climate change can be avoided by preserving ecosystem services through (i) limiting the level of climate change and/or (ii) removing concomitant stresses such as overgrazing, fishing, habitat destruction, and pollution. Most of the literature currently focuses on strategy (ii), and there is limited information about the exact levels of climate change that specific coupled socio-economic systems can withstand. Examples of strategy (ii) include maintaining the resilience of coral reefs or pelagic cephalopod populations by the removal of stress from fishing (Andre *et al.,* 2010; Anthony *et al.,* 2011; section 6.3.5.1, section 30.6.3.1) or expanding protected area networks in the tropics (Brodie *et al.,* 2012). Similarly, risks to seabird populations due to climate change impacts on fish (prey) populations could be lessened by reducing concomitant fishing stress (Cury *et al.*, 2011). In some cases, it is possible to use management to reverse the crossing of a tipping point, for example by adding an appropriately chosen amount of sediment to a submerged salt marsh (Stagg and Mendelssohn, 2010). However, strategy (ii) generally becomes ineffective once climate changes beyond a certain threshold that is not well known and varies across socio-ecological system. Furthermore, some systems may contain multiple thresholds (Renaud *et al.*, 2010) that may be crossed as stresses increase.

Other literature focuses more generally on the need for adopting a resilence-based management approach in both marine and terrestrial ecosystems (Walker and Salt 2006; Lubchenko and Petes 2010; Allen *et al.* 2012; Selig *et al.,* 2012). For regime shifts in ecosystems, a high level of biodiversity increases ecosystems' resilience and can enable them to recover after crossing a tipping point (Brierley *et al.*, 2009; Lubchenko and Petes, 2010). Regime shifts have already occurred in several marine food webs (Byrnes *et al.*, 2007; Alheit *et al.*, 2009, Green *et al.,* 2008, section 6.3.5.1) as a result of (observed) changes in sea surface temperature, changes in salinity due to change in runoff, and (separately) natural climate variability, and/or overfishing, showing how future climate change will analogously affect species composition and hence ecosystem functioning and potentially biogeochemical cycles. Removal of concomitant stress such as nutrient loading can reduce the chance of a regime shift (Jurgensone *et al.*, 2011) for example in coral reef ecosystems (De'ath *et al.*, 2012). Appropriate ecosystem monitoring that looks for a slowing down in the recovery of systems from small changes (Nes and Scheffer, 2007) or measures whether an appropriate indicator value is too low or too high, (Biggs *et al.,* 2008) may give warning that a system is a approaching a regime shift, allowing intervention of type (ii) above to be implemented (Brock and Carpenter, 2010; Cuttal and Jayaprakash, 2008). Indicators that could be used for such monitoring have been identified for the desertification process in the Mediterranean (Alados *et al.*, 2011) and for landscape fire dynamics (Zinck *et al.*, 2011, McKenzie and Kennedy, 2012).

19.7.5. Limits to Adaptation

Chapter 16.2 and 16.5 provide a thorough assessment of the literature on limits to adaptation. Discussions are beginning on the nature of such limits, e.g. in terms of different dimensions of the limits of adaptation, including financial or economic limits to adapt, but also social and political or cognitive limits of adaptation. Limits of adaptation (see e.g. Adger, 2009) are also recognized in terms of specific geographies, for example small island developing states and their limited ability to adapt to increasing impacts of sea level rise, the limits of adaptation of urban agglomerations in low-laying coastal zones (see e.g. Birkmann, 2010b), or in relation to loss of water supplies as a result of glacier retreat (Orlove, 2009). Overall, limits of adaptation have a close link to key vulnerabilities and key risks, since limits of adaptation are influenced by key vulnerabilities, such as identified in the cross-chapter table 19.3, and contribute to the development of key risks.

Frequently Asked Questions

FAQ 19.1: How does climate change interact with and amplify pre-existing risks?

The size of a risk depends on the probability that people or societies will be exposed to a triggering weather or climate-related trend or event and their vulnerability to damage and loss occurring as a result. For example, people living near certain coastal areas are more likely to be exposed to storm surge from tropical cyclones than those living

inland. Exposure to potentially damaging physical events and vulnerability to those damages taken together constitute risk.

Climate change can amplify climate risks by changing the likelihood that damaging physical events or trends will occur, altering patterns of exposure of vulnerable people and societies to such events, or increasing their vulnerability to a number of risks not directly related to climate change. For example, older populations are more vulnerable than younger ones to a variety of climate and non-climate stresses. The increased incidence of extreme heat as the climate warms will further raise the relatively high risk of death from heat stress in this vulnerable group and simultaneously make them yet more vulnerable to other stresses like air pollution (absent anticipatory adaptation measures like increased availability of air conditioning). An example of indirect effects of climate change on risk is provided by the interaction of vulnerability due to poverty and associated risk of malnutrition with climate change abatement policy. Poverty increases people's vulnerability to malnutrition during periods of rising grain prices. Climate change has already given rise to government policies encouraging expansion of biofuel production based on fermentation of corn. Resulting increases in demand for corn contribute to higher corn prices and may indirectly increase incidence of malnutrition in vulnerable populations.

FAQ 19.2: How can climate change at one location cause impacts at another, distant location?

Impacts of climate change are felt locally and directly where the events and trends related to a changing climate occur. However, such impacts may cause responses on the part of humans, societies, and ecosystems and species which reverberate elsewhere and cause important indirect impacts at great distance from the initial climate impact. For example, a changing climate may lead to reduced crop productivity in some regions, reducing agricultural commodities supplied from that region and increasing demand for and price of the same or substitute crops grown in distant regions. In that case, a distant, indirect impact is transmitted by price changes in the global commodities markets. In a second example, people may migrate in response to impacts of climate change such as drought, leading to potential for both positive and negative consequences at receiving regions that may be far from the point of origin of the migrants. (Chapter 19.3, 19.4)

[Placeholder for a schematic figure here illustrating distant, indirect impacts]

FAQ 19.3: Does science provide an answer to the question of how much warming is acceptable?

The question of how much warming is acceptable is raised in Article 2 of the UN Framework Convention on Climate Change (UNFCCC). The criteria for determining what constitutes, in the words of Article 2, "dangerous anthropogenic interference with the climate system" are based both on science and human values. Science can determine, within a range of uncertainty, how much monetary loss might occur if tropical cyclones grow more intense or heat waves more frequent, for example. But comparing damages across communities, countries, or larger regions depends on how each political, social, or cultural entity values the losses. Comparing loss of property to loss of life is even more difficult and controversial, particularly when damage to future generations is involved. The purpose of this chapter is to highlight key risks and vulnerabilities that science has identified; however it is up to people and governments to determine how these potential impacts should be valued. For example, agreements reached by governments since 2009, meeting under the auspices of the UNFCCC, have recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius" (Chapter 19.1, UNFCCC, Copenhagen Accord).

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Table 19-1: Emergent risks related to biofuel production as a mitigation strategy.

Issue number	Issue description	Nature of emergent risk	Reference
(i)Biofuel production	Potential for enhancement of greenhouse gas emissions	Does not contribute to mitigation	Wise *et al.,* 2009 Mellilo *et al*., 2009 Khanna *et al.,* 2011
(ii) Policies targeting only fossil carbon	Competition for land, reducing natural forest and impacting on biodiversity	Emerging risk of biodiversity loss due to mitigation-driven land use change	Wise *et al*., 2009 Mellilo *et al*., 2009 Lapola *et al*., 2010 Fargione *et al*., 2010
(iii) Food/fuel competition for land	Competition for land driving up food prices and impacting on numbers of people at risk of hunger	Emerging risk of food insecurity due to mitigation-driven land use change	Hertel *et al.,* 2010, Searchinger *et al.,* 2008
(iv) Biofuels production effects water resources	Competition for water impacting on biodiversity and food cropping	Emerging risk of biodiversity loss and food insecurity due to mitigation-driven water stress	Fargione *et al*., 2010, Fingerman *et al*., 2010
(v) Land conversion causes air pollution	Potential for increased production of tropospheric ozone	Emerging risk of biodiversity loss and food insecurity due to mitigation-driven damage caused by tropospheric ozone	Hewitt *et al*., 2009, Cancado *et al*., 2006
(vi) Fertilizer application	Potential for increased emissions of N2O	Offsets some benefits of other mitigation measures	Donner and Kucharik 2008, Searchinger *et al*., 2008, Fargione *et al*., 2010
(vii) Invasive properties of biofuel crops	Potential to become an invasive species	Unintended consequences that damage agriculture and/or biodiversity	Barney and Ditomaso 2008, Council for Agricultural Science and Technology 2007, Raghu *et al*., 2006

NOTES:

(i) First-generation biofuel consumption has been projected to increase by up to 170-220% by 2020 and up to 250-620% by 2030 (IEA, 2009), with the larger numbers corresponding to the implementation of a limit of 450ppm for CO_2 concentrations. Second generation biofuels are thought not to be commercially viable for large scale production until after 2020. Biofuels presently occupy about 2.2% of global cropland (33 million ha), whilst the area under cultivation itself is expanding at some 3.4 million ha/yr (FAO, 2010) due to rising demand for food. Hence, such large projections for increase in biofuel production have profound implications for land use. If this biofuel induced land use change removes primary forest, the net contribution of the biofuel cropping towards climate change mitigation may be negative. The potential scope of the impact on a global scale is revealed in one study (Wise *et al*.,2009) that considers a scenario leading to conversion of more than 40% of global land area to biofuel production by 2095.

(ii) Large scale conversion of natural forest induced by a carbon tax that does not include terrestrial carbon would have a severe impact on biodiversity (see section 19.4.3.3.) through the destruction of most remaining natural ecosystems (Wise *et al*., 2009). In Brazil, the biofuel expansion resulting from such a scenario would be expected to impinge upon the Cerrado, the Amazon and the Atlantic rainforest all three of which have high biodiversity and high levels of endemism (Lapola *et al*., 2010). Concessions of large areas for biofuel production have been made in the Brazilian Amazon, Papua New Guinea, and Madagascar, all of which are biodiversity hotspots (Koh et al. 2009). Biodiversity is reduced by about 60% in U.S. corn and soybean fields and by about 85% in Southeast Asian oil palm plantations compared to unconverted habitat (Fitzherbert *et al*., 2008; Fletcher *et al*., 2010; Fargione, 2010).

(iii)Displacement of agricultural land for biofuel crops would influence world food supply and prices (Hertel *et al*., 2010, Searchinger *et al*., 2008), as actually occurred during the food price crisis of 2007/2008 (Pimentel, 2009), thus increasing risks of malnutrition. A new assessment of agricultural land availability projects that by 2050, substantial areas of agricultural land will be lost to urbanization, desertification, sea level rise and increasing salt water intrusion (Foresight 2011) which will act to increase competition between cropping for food and biofuels. Mellilo *et al*. (2009) project that up to twice as much carbon loss can occur as result of this indirect land use change, than from the direct land use change associated with biofuel production. Some biofuel feedstocks such as wastes, residues, cover crops, and forest thinnings (Tilman *et al.,* 2009) are not in competition with cropland.

(iv) The water requirements of many biofuel crops are substantial (Fargione *et al*., 2010, Fingerman *et al*., 2010) and hence there would be potential for conflict with efforts to allocate water for domestic, industrial, agricultural and natural wetlands particularly where irrigation is required (Yang *et al*., 2012, Poudel *et al*., 2012).

(v) Where rainforest is converted to oil palm plantations, or where land is converted to sugarcane ethanol production, emissions of the precursors of tropospheric ozone increase (Hewitt *et al*., 2009, Cancado *et al*., 2006).

(vi) Where biofuels displace nitrogen-fixing crops such as soybean, fertiliser application will increase, leading to increased N_2O emissions and nitrogen runoff into rivers and oceans (Donner and Kucharik 2008). At the same time, displacement of food crops, in combination with reduced yields due to climate change impacts, would encourage farmers to increase yields through application of larger amounts of fertiliser, particularly in countries where there is a supply shortfall (Deryng *et al*., 2011) which in turn increases greenhouse gas emissions.

(vii) Land use change also has direct effects on local climate: for example, new urban developments caused an intensification and expansion of the area experiencing extreme temperatures, mainly increasing nighttime temperatures, by as much as 10 K. (Grossman and Clarke 2010).

(viii) Traits that make a plant a good candidate for biomass production also make it a potential invasive species (Barney and Ditomaso 2008; Council for Agricultural Science and Technology, 2007; Raghu *et al*., 2006). This could result in damage to nearby ecosystems or agricultural systems.

Table 19-2: Key risks from large temperature rise.

Sector	**Region**	**Key Risk**
Agriculture	Globe	Decline in agricultural production
Water	Globe	20-30% increase in exposure to water stress; 40-80% declines in runoff in Danube, Mississippi, Amazon and Murray-Darling rivers; Drought affected area 44+/-6% of earth's terrestrial surface
Ecosystems	Tropics	Widespread coral reef mortality
Ecosystems	Globe	Climate space is lost upon 10-48% earth's surface; 60% plants and 33% animals projected to lose >50% of climatic range;
Health	Globe, Urban Areas	To be provided with next draft

Table 19-3: A selection of the hazards/stressors, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26). Key risks are determined by hazards and stressors interacting with vulnerability and exposure of human systems, infrastructure, and ecosystems or species. The table underscores the complexity of risks determined by various climatic hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, demographic changes or tolerance limits of species and ecosystems which often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g. climate change, urbanization and demographic changes) in combination and in specific development context (e.g. in low-laying coastal zones), can generate new systemic risks that go far beyond existing adaptation and risk management capacities, particularly in highly vulnerable regions.

Examples of Hazards/Stressors, Key Vulnerabilities, Key Risks and Emergent Risks (using input from chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26)			
Hazard/ Stressor	**Key vulnerabilities**	**Key risks**	**Emergent risks**
Terrestrial and inland water systems (chapter 4)			
Rising air, soil, and water temperature	Exceedence of eco-physiological climate tolerance limits of species, increased viability of alien organisms	Loss of native biodiversity, increase in alien organism dominance	Cascades of native species loss due to interdependencies
	Epidemiological response to spread of temperature-sensitive vectors (insects)	Novel or much more severe pest and pathogen outbreaks	Interactions between pest, drought and fire interactions can lead to new risks and large negative impacts on ecosystems
Change in seasonality of rain	Vulnerability of plants and ecosystem services, due to mismatch of plant life strategy to growth opportunities	Changes in plant functional type mix leading to biome change with respective risks	Fire-promoting grasses and summer fuels in winter-rainfall areas
Ocean Systems (chapter 6)			
Rising water temperature, increase of (thermal and haline) stratification, and marine acidification [6.1.1] *(also Chapter 24)*	Tolerance limits of endemic species surpassed, increased abundance of invasive organism, high vulnerability of warm water coral reefs and respective ecosystem services for coastal communities [6.2.2, 6.2.5]	Loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms, loss of coral cover and associated ecosystem with reduction of biodiversity [6.3.2]	Enhancement of risk due to interactions, e.g., acidification and warming on calcareous organisms [6.3.5]
	Shifted productivity zones and species distribution ranges, largely from low to high latitudes [6.1.3], shifting fishery catch potential with species migration [6.5.2, 6.5.3]	Unknown productivity and services of new ecosystem types [6.4, 6.5.3]	Enhancement of risk due to interactions of drivers, warming, hypoxia, acidification, new biotic interactions [6.3.5, 6.3.6]
Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication [6.1.1]	Hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates [6.2.5]	Loss of larger animals and plants, shifts to hypoxia adapted, largely microbial communities with reduced biodiversity [6.3.3]	Enhancement of risk due to expanding hypoxia in warming oceans [6.3.5]
Enhanced harmful algal blooms in coastal areas due to rising water temperature	Increasing vulnerability of important ecosystems and valuable services due to	Enhanced frequency of dinoflagellate blooms and respective losses and	Disproportionate enhancement of risk due to interactions of various

[6.4]	already existing multiple stresses [6.3.5, 6.4]	degradations of coastal ecosystems and ecosystem services [6.4]	stresses [6.3.5]
Food security and food production systems (chapter 7)			
Rising average temperatures and more frequent extreme temperatures.	All elements of the food system from production to consumption vulnerable for key grain crops.	Crop failures, breakdown of food distribution and storage processes.	Increase in the global population to ca. 9 billion combined with rising temperatures and other trace gases such as ozone affecting food production and quality. Upper temperature limit to the ability of some food systems to adapt. [7.1, 7.2, 7.4, 7.5]
Urban areas (chapter 8)			
Inland flooding	Urban areas with large numbers of poor, uninsured people exposed to flood events including low-income informal settlements. Environmental health consequences from overwhelmed, aging, poorly maintained and inadequate urban drainage infrastructure and widespread impermeable surfaces. Inadequate local governance. Increased mosquito and water borne diseases.	Increasing urban flooding with increasing volume and velocity of flood waters on the one hand and increasing vulnerability on the other leads to key risks particularly in urban areas with large number of poor and exposed to flooding.	Larger and more frequent flooding impacting much larger population. Impacts reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts and the creation of high risk/high poverty spatial traps.
Coastal flooding (including sea level rise and storm surge)	High concentrations of people, businesses and physical assets including critical infrastructure in low-lying and unprotected coastal zones including low-elevation coastal zones in addition to vulnerability noted in previous example.	Flooding interacts with highly vulnerable people and areas that are likely lead to multiple negative consequences and hence key risks. Storm surges often causing the most serious floods	Sea level rise increasing risk over time, increasing concentration of population and economic activities on the coasts. Reaching the limits of insurance; shift in risk management from the state to those at risk leading to consequences noted above.
Heat and cold including Urban Heat Island (UHI)	Increasing urban population of infants, young children, older age groups, expectant mothers, people with compromised immune system at risk from higher temperatures (especially in heat islands) and unexpected cold spells. Inability of local organizations for health, emergency services and social services to adapt to new risk levels.	In heat waves with higher or more prolonged high temperatures or cold spells - mortality and morbidity increasing, including shifts in seasonal patterns and concentrations.	Extension and variability of heat waves and less frequent and thus unexpected cold spells, increasing risks over time for most locations. Low-income groups often facing greatest difficulties avoiding risks
Water shortages and drought in urban regions	Urban dwellers lacking water piped to their premises. Urban areas with water	Loss of functionality to urban water provision services and industry with	Urban viability may be threatened by loss of freshwater sources –

	shortages and constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural-urban linkages. Dependence on water resources in energy production systems.	human and economic impacts. Damage to urban ecology and its utility including urban and peri-urban agriculture.	including many cities dependent on glacier meltwater
Changes in urban meteorological regimes lead to enhanced air pollution	Health impacts from increases in exposure to high pollution levels with impacts most serious among physiologically susceptible populations. Urban governments' not implementing pollution controls.	Mortality and morbidity, lowered quality of life. May undermine the competitiveness in global cities to attracting key workers and investment.	Complexity and compounding of health crises.
Geo-hydrological hazards (salt water intrusion, mud/landslides, subsidence)	Vulnerability of local structures and networked infrastructure impacted by systems-level environmental change. Inability of many low-income households to move to safer housing on safer sites	Increasing risk of damage to networked infrastructure (water, sanitation, drainage, communications. transport, energy), property and human loss due to geo-hydrological hazards and the vulnerability of people and local structures.	Potential for large local and aggregate impacts via knock on effects for urban activities and wellbeing.
Storms with higher wind speeds	Sub-standard buildings and physical infrastructure and the services and functions they support. Old and hard-to-retro-fit buildings and infrastructure in cities. Local government unable or unwilling to give attention to disaster risk reduction	Damage to dwellings, businesses and public infrastructure. Loss of function and services. Challenges to recovery, especially where insurance is absent.	Challenges to individuals, businesses and public agencies where the costs of retrofitting are high leading budgetary competition and potential for tensions between development and risk reduction investments.
Changing hazard profile including novel hazards and new multi-hazard complexes	Newly exposed populations and infrastructure, especially those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks.	Risks from failures within coupled systems e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications, psychological shock from unanticipated risks.	Loss of faith in risk management institutions. Potential for large events that are magnified by a lack of preparation and capacity to respond.
Compound slow-onset hazards including rising temperatures and variability in temperature and water availability	Large sections of the urban population in low- and middle-income nations with livelihoods or food supplies dependent on urban and peri-urban agriculture.	Damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture and other productive or protective eco-system services. Knock-on impacts for urban and peri-urban livelihoods and urban health.	Collapsing of peri-urban economies and ecosystem services with wider implications for urban service provision and disaster risk reduction.
Changes in temperature and precipitation leading to	Large urban population at risk from food and	Increases in exposure to these diseases	Growing incapacity of public health system to

changed conditions for disease propagation	waterborne diseases and to malaria, dengue and other vector borne diseases		address this and simultaneous increase in exposure to other impacts such as flooding
Rural areas (chapter 9)			
Drought in pastoral areas, changes in rangeland composition [9.3.3.1, 9.3.5.3.1]	Encroachment on pastoral rangelands, inappropriate land policy, misperception and undermining of pastoral livelihoods, conflict over natural resources, all driven by remoteness and lack of voice.	Inability to cope with drought, leading to famine. Changes in herd dynamics. Loss of revenues from livestock trade.	Impacts on livelihoods through animal disease in pastoral areas.
Effects of climate change on fish stocks; impacts of tropical storms on settlements and fishing gear. [9.3.3.1, 9.3.5.3.3]	Artisanal fisheries affected by pollution, mangrove loss, competition from aquaculture, neglect of sector by governments and researchers, complex property rights.	Declining catches and incomes for artisanal fisherfolk.	Reduced dietary protein for those consuming artisanlly-caught fish.
Water shortages and drought in rural areas [9.3.5.2.1.]	Rural people lacking access to drinking and irrigation water. Lack of capacity and resilience in water management regimes (institutionally driven).	Reducing agricultural productivity and/or income of rural people, mostly those depending on irrigated agriculture or high-yield varieties. Food insecurity.	Impacts on livelihoods driven by interaction with other factors (water management institutions, water demand). Human health.
Human health (chapter 11)			
Increasing frequency and intensity of extreme heat *(also chapter 19)*	Older people living in cities are most vulnerable to heat waves, and their population projected to triple from 2010-2050.	Increased mortality and morbidity during heat waves, particularly in those with pre-existing conditions	Overloading of health and emergency services. Mortality, morbidity and productivity loss, particularly in manual workers in hot climates
Increasing temperatures, increased variability in precipitation	Food insecurity translates into malnutrition, which is among the largest disease burdens in poorer populations.	Progress in reducing mortality and morbidity from malnutrition may slow or reverse and constitutes a new key risk	Combined impacts of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequity, and on-going food insecurity for the poor
Increasing temperatures, changing patterns of precipitation	Water- and vector-borne disease highly sensitive to meteorological conditions	Changing spatial and temporal distribution hampers disease control, exposes non-immune populations	Rapid climate and other environmental change may promote emergence of new pathogens
Increased variability in precipitation	Diarrhoea facilitated by higher temperatures, unusually high or low precipitation	Progress in reducing diarrhoea morbidity is compromised	Increased rate of failure of water and sanitation infrastructure leading to higher diarrhoea risk
Livelihood and poverty (chapter 13)			
Changing rainfall patterns (temporally and spatially)	High dependence on rain-fed agriculture. Little access	Crop failure, food shortage, severe famine	May coincide with global food insecurity or periods of

	to alternative modes of income.		excessive global food prices which means that coping strategies may not work. Adaptation mechanisms such as crop insurance (risk spreading) may collapse.
Soaring demand (and prices) of biofuels due to climate change policies.	Unclear and/or insecure land tenure arrangements.	Risk of dispossession of land due to "land grabbing" in developing countries.	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production.
Increasing frequency of extreme events (droughts, floods). For example if 1:20 year drought/flood becomes 1:5 year flood/drought.	Livelihoods subject to damage to their productive assets (e.g. in case of droughts – herds of livestock; if floods – dykes, fences, terraces).	Risk of the loss of livelihoods and harm due to shorter time for recovery between extreme. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years.	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.
Emergent risks and key vulnerabilities (chapter 19)			
Warming and drying (degree of precipitation changes uncertain) [AR5 WGI TS.5.3, WGI SPM, WGI 11.3, WGI 12.4]	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; socio-cultural constraints on some adaptation options [19.2.2, 19.3.2.2, 19.6.1.1, 19.7.5]	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition limited coping and adaptation options increase the risk of harm and loss. [19.3.2.2]	Negative outcomes to sending and/or receiving regions from migration of populations due to limits on agricultural productivity and livelihoods [19.3.2.2, 19.4.2.1]
Changes in regional and seasonal temperature and precipitation over land [AR5 WGI TS.5.3, WGI SPM, WGI 11.3, WGI 12.4]	Dependence of communities on ecosystem services [19.2.2.1, 19.3.2.1]	Large scale species richness loss over most of the global land surface. 57±6% of widespread & common plants and 34±7% of widespread & common animals likely to lose ≥50% of their current climatic range by the 2080s leading to loss of services [19.3.2.1]	Widespread loss of ecosystem services: including *provisioning*, such as food and water; *regulating*, such as the control of climate and disease; *supporting*, such as nutrient cycles and crop pollination; and *cultural*, such as spiritual and recreational benefit [19.3.2.1, 19.6.3.4]
Africa (chapter 22)			
Increasing Temperature	Health of exposed and vulnerable groups (increased exposure to heat, change in the transmission dynamics of vector-borne diseases)	Increase in disease burden – changes in the patterns of infection Decrease in outdoor worker productivity due to high temperature, increase in heat related morbidity and mortality	Emerging and re-emerging disease epidemics
	Vulnerability of aquatic	Loss of aquatic ecosystems	

	systems and vulnerability of aquatic ecosystem services due to increased water temperatures	and risks for people who might depend on these resources	
Extreme Events, e.g. floods and flash floods	Vulnerable and exposed urban areas, particularly in informal settlements	Increasing harm and losses due to water logging in terms of sudden volumes of rain	Due to water logging and contamination, compounded increase of the risk of epidemics
Europe (chapter 23)			
Extreme weather events *(also Chapter 19)*	Limited coping and adaptive capacity as well as high sensitivity of different sectors, e.g. transport, energy and health sector	Stress on multiple sectors can cause systemic risks due to interdependencies between the different sectors	Disproportionate intensification of risk due to increasing interdependencies
Climate change increases the spatial distribution and seasonality of pests and diseases	Vulnerability of plants and animals exposed to pests and diseases	Increases in crop losses and animal diseases or even fatalities of livestock	Increasing risks due to limited response options and various feedback processes in agriculture, e.g. use of pesticides or antibiotics to protect plants and livestock increases resistance of disease vectors
Extreme weather events and reduced water availability due to climate change	Low adaptive capacity of power systems might lead to limited energy supply as well as higher supply costs during such extreme events and conditions	Increasing risk of power shortages due to limited energy supply, e.g. of nuclear power plants due to limited cooling water during heat stress	Continued underinvestment in adaptive energy systems might increase the risk of mismatches between limited energy supply during these events and increased demands, e.g. during a heat wave
Asia (chapter 24)			
Thawing of permafrost due to rising temperature in northern Asia.	Existence of structures and infrastructures on the permafrost and high dependences of civil life on them	Instability of or damages to the structures and infrastructures	Projected exacerbation of instability of residential buildings, pavements, pipelines used to transport petroleum and gas, pump stations and extraction facilities
Projected increase in frequency of various extreme events (heat-wave, floods and droughts) and sea level rise *(also Chapter 19)*	Convergence of livelihood and properties into coastal megacities, especially into area that is not protected against natural hazards sufficiently	Loss of human life and life stocks due to coastal floods accompanied by increasing vulnerabilities caused by occurrence of other extreme events like heat-wave and droughts	Projected increase in disruption of basic services such as water supply, sanitation, energy provision, and transportation system, which themselves could increase vulnerabilities
Australasia (chapter 25)			
Warming and drying in southern Australia and parts of New Zealand (uncertain degree of precipitation change) [25.2, Table 25-1]	Increasing build-up of combustible material in CO_2-enriched environment, increased ignition rate and combustibility, increasing exposure of human systems to these changes [25.6.1,	Increased damages to ecosystems and settlements and risks to human life from wildfires [25.6.1, Box 25-6, 25.10.2]	Increasing risk from compound extreme events across time, space and governance scales, and cumulative adaptation [25.10.2, 25.10.3, Box 25-9]

	Box 25-6]		needs
Warming and increased temperature high extremes in Australia [25.2, Table 25-1, Figure 25-5]	Urbanization, aging of population and vital infrastructure [25.3, Box 25-9, 25.10.2]	Increase in morbidity, mortality and infrastructure failure during heat waves [25.8.1, 25.10.2]	
Potential for sea level rise beyond 2100 exceeding 1m [25.2, AR5 WGI Chapter 13]	Long lifetime of coastal infrastructure, concentration and further expansion of coastal population and assets; conflicting priorities and time preferences constraining adaptation options; limited scope for managed retreat in highly developed areas [25.3, Box 25-1]	Widespread damages to coastal infrastructure and low-lying ecosystems [Box 25-1, 25.10.2]	
North America (chapter 26)			
Increases in frequency and/or intensity of extreme events, such as hurricanes, river and coastal floods, heat waves and droughts [26.2] *(also Chapter 19)*	Declining state of physical infrastructures in urban areas as well as increases in income disparities [26.7]	Risk of serious harm and losses in urban areas, particularly in coastal environments due to enhanced vulnerabilities of social groups and physical systems combined with the increases of extreme weather events [26.8]	Inability to reduce vulnerability in many areas results in increase in risk greater than change in physical hazard [26.8]
Higher temperatures, decreases in runoff and lower soil moisture due to climate change [26.2, 26.3]	Increasing vulnerability of small landholders in agriculture [26.5]	Increased losses and decreases in agricultural production increase food and job insecurity for small landholders and social groups in that region [26.5]	Increasing risks of social instability and local economic disruption due to internal migration [26.2, 26.8]

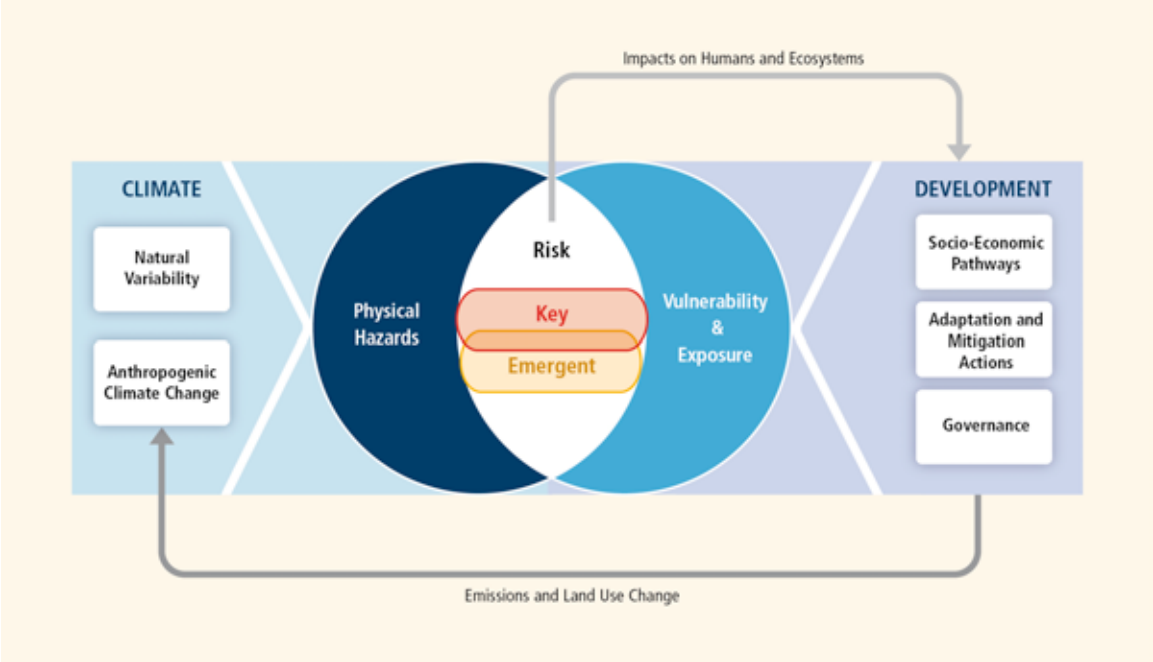

Figure 19-1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. It underscores that risks are a product of a complex interaction between physical hazards associated with climate change and climate variability on the one hand, and the vulnerability of a society or a social-ecological system and its exposure to climate-related hazards on the other. The definition and use of "key" are indicated in Box 19-2 and the glossary. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions. Both the changes in the climate system (left side) and the development processes (right side) are key drivers of the different core components (vulnerability, exposure, and physical hazards) that constitute risk (modified version of Figure 1, IPCC, 2012.

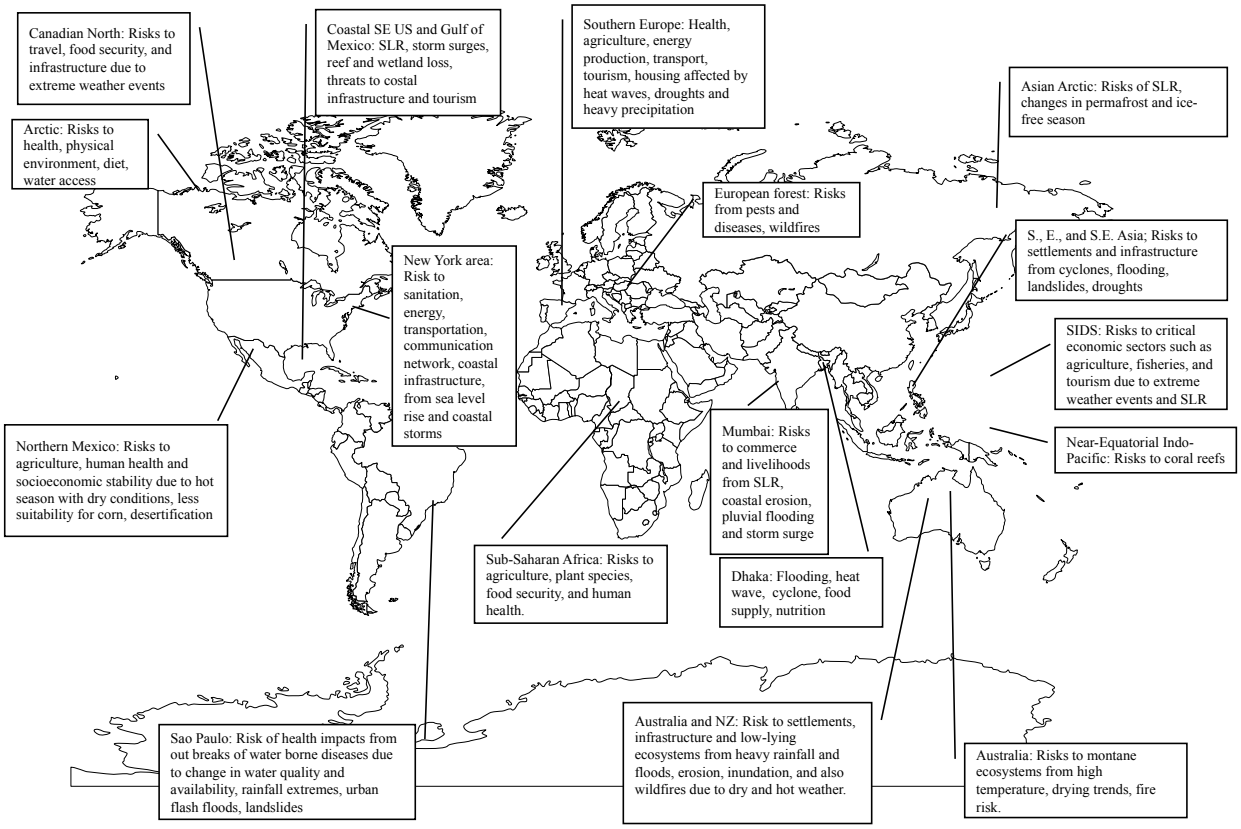

Figure 19-2: Some salient examples of multi-impacts hotspots identified in this assessment.

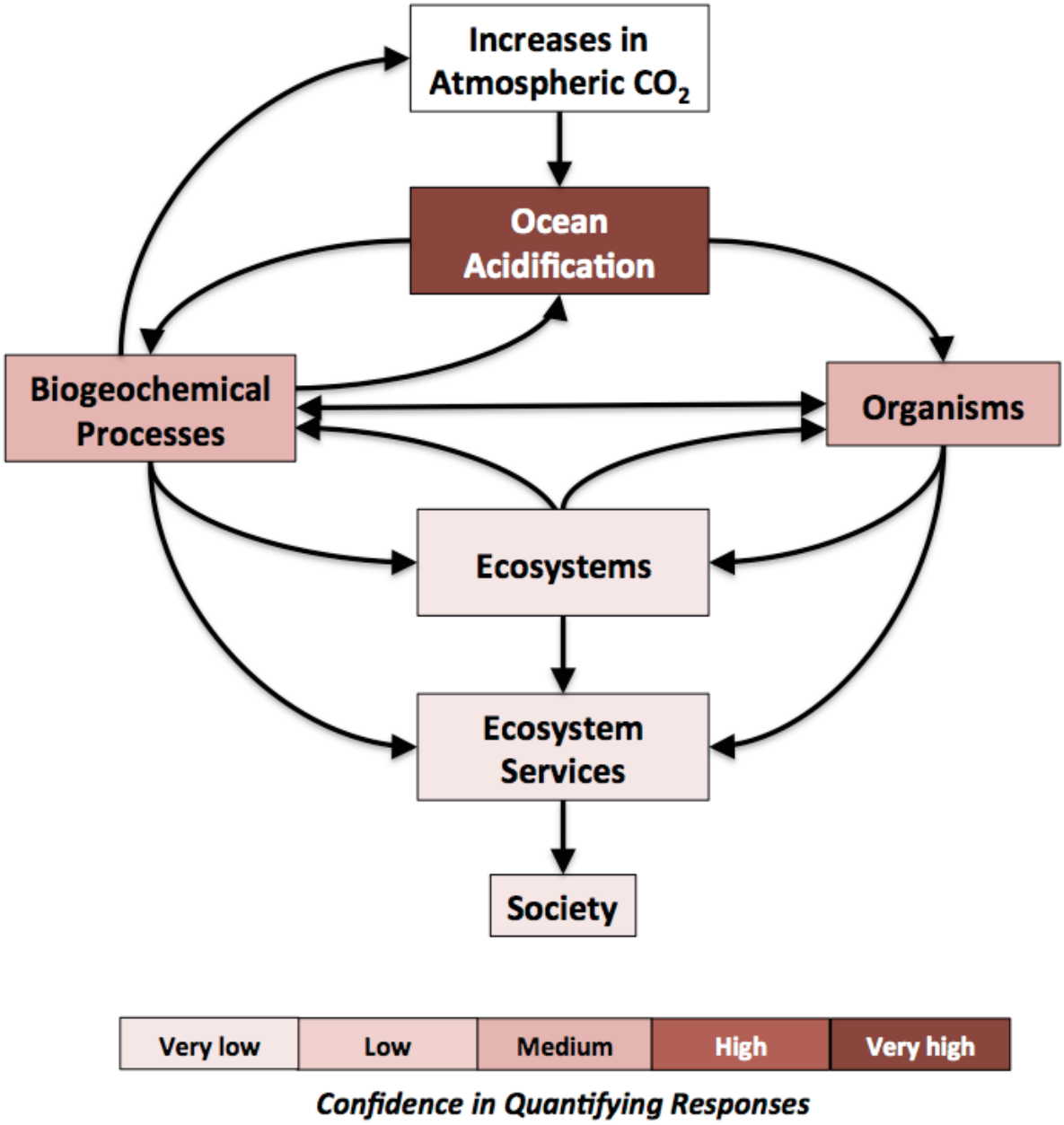

Figure 19-3: The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. Confidence in quantifying these effects (as summarized from WG2 Chapter 6) decreases with each step along the pathway, and is very low for effects on ecosystems, ecosystem services, and society.

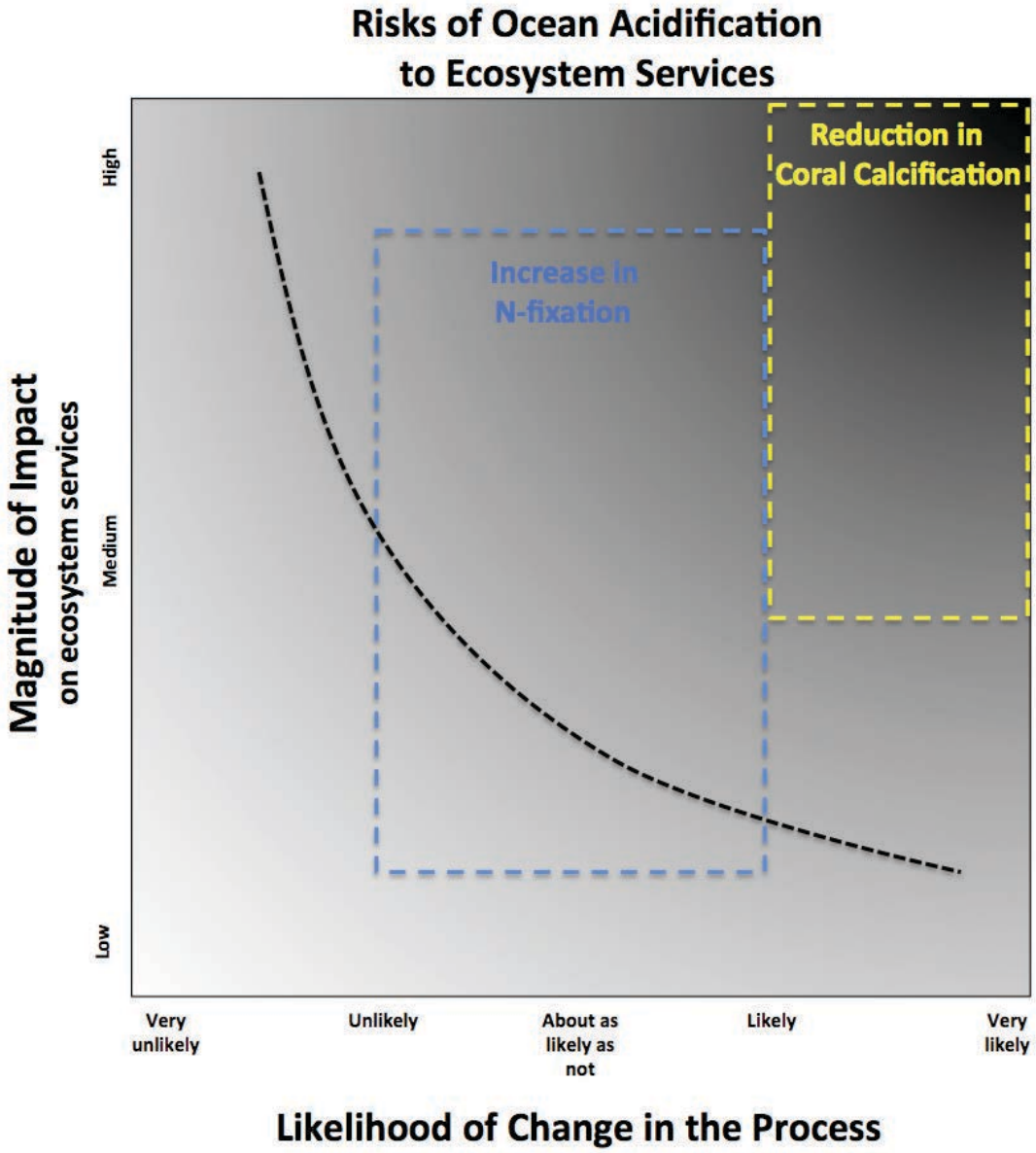

Figure 19-4: Risks of ocean acidification to ecosystems services through two effects on biogeochemical processes: (1) reductions in calcification rates (of corals) and (2) increases in nitrogen-fixation rates. Assessments are based on the estimated *likelihood* that the process will be affected by ocean acidification (horizontal axis) and the *magnitude* of the impacts on associated ecosystem services (vertical axis) should the process be affected. Heights and widths of boxes indicate the range of uncertainty in the magnitude of impacts on ecosystem services and likelihood of change in the process, respectively. Heights are greater than widths due to the lower confidence in responses of ecosystems and their services (Figure 19-3). Judgments are based on impacts expected with atmospheric CO_2 levels of 2-3x preindustrial levels (560-840 ppmv). This figure is meant to be broadly illustrative: with sufficient information Low, Medium, and High magnitudes of impacts would be defined quantitatively. The shading of the box represents the risk (*likelihood* x *magnitude*) to ecosystem services with the dashed contour showing the line of equal risk; the area above and to the right of this line is broadly indicative of key risks. Thus, the reduction in calcification due to ocean acidification is already considered a key risk to some ecosystem services, while the limited evidence regarding the nitrogen fixation response and its impacts implies that it may or may not become a key risk as uncertainty is reduced.

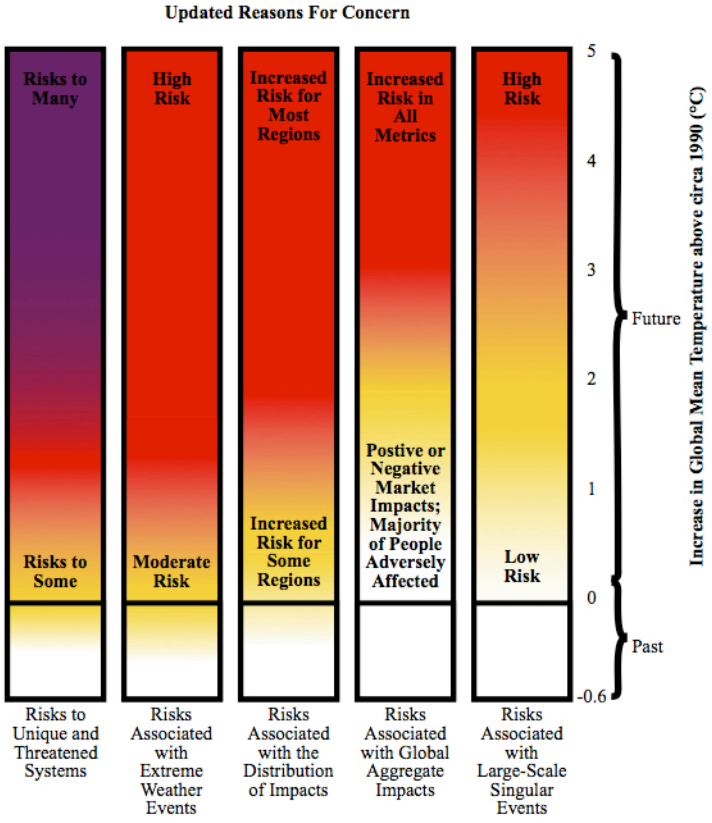

Figure 19-5: The dependence of risk associated with a Reason for Concern (RFC) on the level of climate change, updated from TAR and Smith *et al.* (2009). The color scheme indicates the additional risk due to climate change (with white to purple indicating the lowest to highest level of risk, respectively). The levels of risk illustrated reflect the judgments of Chapter 19 authors. Purple color, introduced here for the first time, reflects the assessment that unique human and natural systems tend to have very limited adaptive capacity (Chapters 4, 24), and hence we have *high confidence* that climate change impacts would outpace adaptation for many species and systems if a global temperature rise of 2°C were exceeded.

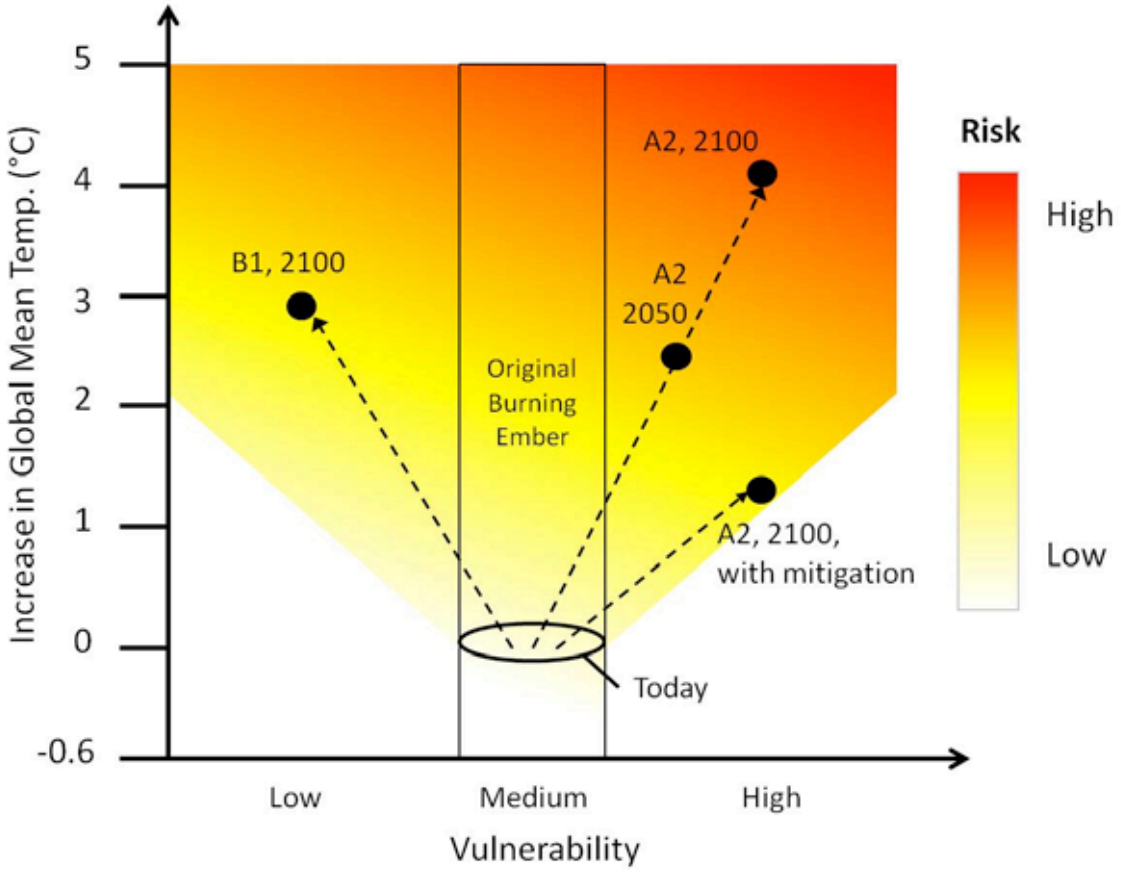

Figure 19-6: Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and vulnerability of society. This figure is schematic; the degree of risk associated with particular levels of climate change or vulnerability has not been based on a literature assessment, nor associated with a particular RFC. The vulnerability axis is relative rather than absolute: "Medium" vulnerability indicates a future development path in which vulnerability changes over time driven by moderate trends in socio-economic conditions. "Low" and "High" vulnerability indicate futures that are substantially more optimistic or pessimistic, respectively, regarding vulnerability. We assume that judgments made in other burning ember diagrams of the RFCs (Smith *et al.*, 2001, 2009) including Figure 19-5, which do not explicitly take changes in vulnerability into account, are consistent with Medium future vulnerability. Arrows and dots illustrate the use of SRES scenario-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socio-economic conditions over time.

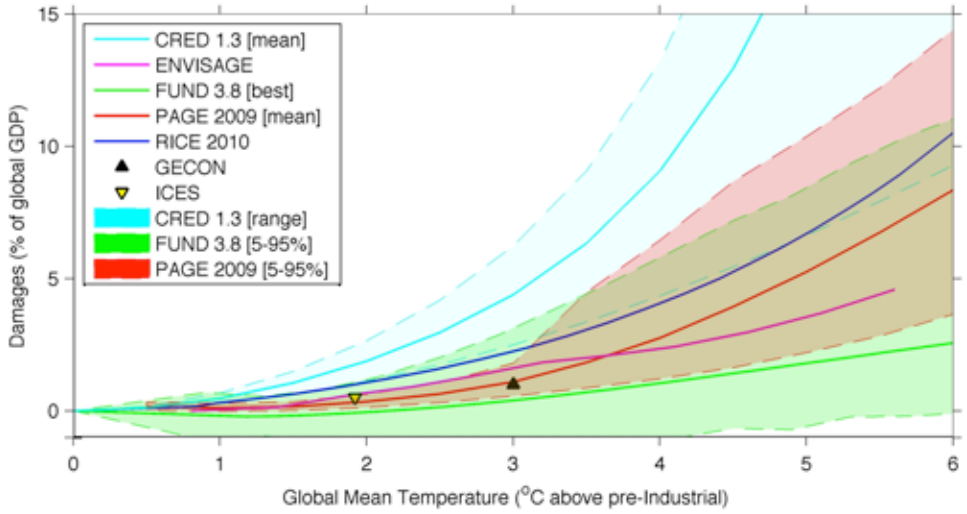

Figure 19-7: Representative global damage estimates, shown as a percentage loss of global output as a function of temperature, from integrated assessment models employing their own reference scenarios. PAGE 2009: (Hope, 2013a, 2013b). FUND 3.8: (Anthoff and Tol, 2010b; Anthoff et al., 2013; Waldhoff et al., 2013). RICE 2010: (Nordhaus, 2010). CRED: (Ackerman et al., 2011). ENVISAGE: (Roson and Mensbrugghe, 2012). GECON: (Nordhaus, 2006). ICES: (Bosello et al., 2012). For PAGE 2009 and FUND 3.8, the shaded region indicates the range spanned by the 5th and 95th percentile of outputs in Monte Carlo mode. The area of overlap between PAGE 2009 and FUND 3.8 is indicated in brown. For CRED 1.3, the shaded region indicates the range spanned by four alternative damage functions. In CRED at 6°C, mean damages are 32% of GDP and the largest of the four damage functions yields 50% loss of GDP.

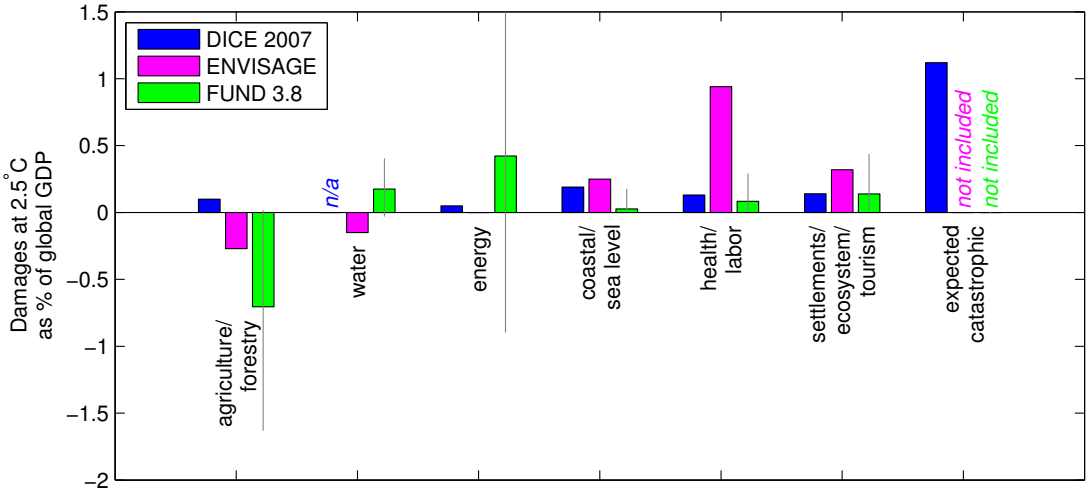

Figure 19-8: Breakdown of damages at 2.5°C above pre-industrial by sector in the DICE 2007 calibration (Nordhaus, 2007, 2008), FUND 3.8 (Anthoff and Tol, 2010b; Anthoff et al., 2013; Waldhoff et al., 2013) modal damages and ENVISAGE (Roson and Mensbrugghe, 2012), reflecting a *low level of agreement* among the integrated assessment models used to estimate global aggregate damages. Note that the DICE calibration does not include damages due to changes in water resources as distinct from temperature impacts on agriculture and forestry, and FUND and ENVISAGE do not include expected catastrophic damages. Representations of changes in energy demand, coastal/sea level impacts, health and labor productivity impacts, and impacts on settlements, ecosystem and tourism are included in all three models. Grey lines span the 5th to 95th percentile of estimates from FUND. The 95th percentile of energy sector damages in FUND is 2.2% of GDP.

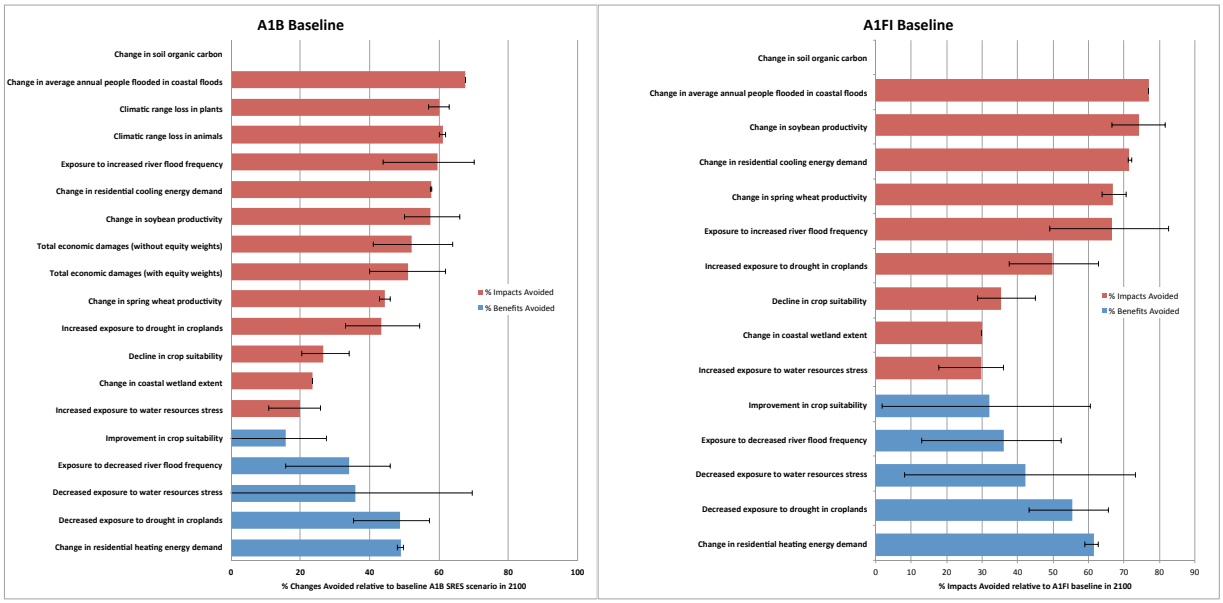

Figure 19-9: Climate change impacts avoided by a mitigation scenario compared to two no-mitigation cases (SRES A1B and A1FI scenarios), showing the uncertainty due to regional climate change impacts projection with 7 Global Circulation Models (GCMs). Since increases and decreases in water stress, flood risks and crop suitability are not co-located and affect different regions, these effects are not combined. From Arnell *et al.*, 2012, Warren *et al.*, in press, Warren *et al.*, submitted.

[Figure 19-10 provided in the next draft]

Figure 19-10**:** relates the categories of mitigation scenario considered in AR5 WGIII, to global temperature outcomes (consistent with the WGI calculations; data taken from Chapter 6 - WGIII). It also relates these temperature outcomes to some salient projected climate change impacts for the different levels of global temperature rise, focusing on those impacts which are less affected by the socioeconomic development pathway.

Chapter 20. Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development

Coordinating Lead Authors
Fatima Denton (Gambia), Thomas Wilbanks (USA)

Lead Authors
Achala C. Abeysinghe (Sri Lanka), Ian Burton (Canada), Qingzhu Gao (China), Maria Carmen Lemos (USA), Toshihiko Masui (Japan), Karen O'Brien (Norway), Koko Warner (Germany)

Contributing Author
Thea Dickinson (Canada)

Review Editors
Suruchi Bhadwal (India), Walter Leal (Germany), Jean-Pascal van Ypersele (Belgium)

Volunteer Chapter Scientist
Sherry B. Wright (USA)

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References

Executive Summary

Climate change calls for new approaches to sustainable development that take into account complex interactions between climate and social and ecological systems. Climate-resilient pathways for development are evolutionary processes for managing change within complex systems. They are rooted in iterative processes of identifying vulnerabilities to climate change impacts; taking appropriate steps (a) to reduce vulnerabilities in the context of development needs and resources and (b) to increase the options available for vulnerability reduction and coping with surprises. Such responses include monitoring emerging climate parameters and their implications, monitoring the effectiveness of vulnerability reduction efforts (including both adaptation and mitigation), and revising risk reduction responses on the basis of continuing learning. Because uncertainties about climate effects and other driving forces affecting development are likely to make conventional development interventions (e.g. specific, multi-decadal strategies and annual or multi-year static plans) non-sustainable over time, fostering climate will require innovative approaches. This process may involve a combination of incremental changes and, as necessary, significant transformations. Such processes and responses will include both climate change risk reduction through mitigation and adaptation and also changes in sustainable development pathways themselves to increase their resilience.

This chapter integrates a variety of complex issues in assessing climate-resilient pathways in a variety of regions at a variety of scales: sustainable development as the ultimate aim, mitigation as the way to keep climate change impacts moderate rather than extreme, adaptation as a response strategy to cope with impacts that cannot be (or are not) avoided, and elements of sustainable development pathways that contribute to climate-resilience. In most cases, vulnerability reduction and appropriate risk management approaches will differ from situation to situation, calling for a multi-scale perspective built solidly on fine-grained contextual realities. But most situations share at least one fundamental characteristic: threats to sustainable development are greater if climate change is substantial than if it is moderate – and opportunities for sustainable development are greater if climate change is moderate rather than substantial.

This chapter's assessment findings are the following. Although they are based on a high level of consensus in source materials and in the expert communities, the amount of supporting evidence is usually limited by the fact that so many aspects of sustainable development and climate change mitigation and adaptation, considered together over periods many decades into the future, are surrounded by issues that are beyond past and current observation and experience. The task of this chapter is to move out into uncharted territory.

Because climate change is a growing threat to development, it is a high priority to identify and pursue climate-resilient pathways for sustainable development (*high confidence*; *high agreement, medium evidence*). Because climate change can no longer be avoided, some impacts on development are already being observed, and they are virtually certain to increase. Added to other stresses on sustainable development, effects of climate change will make sustainability more difficult to achieve for many locations, systems, and affected populations, related to such objectives as poverty reduction, health, and livelihood security; but climate-resilient pathways can improve prospects for sustainable development. [20.2]

Climate-resilient pathways include (a) actions to reduce climate change and its impacts and (b) actions to assure that effective risk management and adaptation can be implemented and sustained (*high confidence*;

***high agreement, medium evidence*).** Adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses. Both kinds of responses are needed, working together to reduce risks of disruptions from climate change. [20.3, 20.4]

In some cases, each of the two categories of responses is likely to benefit the other as well, offering potentials for co-benefits from integration (*moderately high confidence*; *medium high agreement, medium evidence*). Development pathways that are resilient with respect to a wide range of challenges and threats are more likely to be climate-resilient, while climate change risk reduction can contribute to strengthening capacities for risk management in other regards as well. Strategies to achieve each goal have the potential to reinforce the other, but windows of opportunity may narrow with time. [20.2.1, 20.3.3]

Prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation (*high confidence*; *high agreement, medium evidence*). As the magnitude of climate change grows, the challenges to climate resilience grow; and above some high level of climate change, the impacts on most systems would be great enough that climate-resilience is no longer possible for many systems and locations. [20.6.1]

Because climate change vulnerabilities are significant for many areas, systems, and populations, climate-resilient pathways will often require transformations in order to assure sustainable development (*high confidence*; *high agreement, medium evidence*). Significantly large and/or rapid increases in climate extremes and climate-related extreme weather events are less amenable to incremental adaptations to climate change and will often require more transformational change if development is to be sustained without major disruptions. [20.5]

At a global scale, climate-resilient pathways will include both climate change adaptation and mitigation. At sub-global scales, climate-resilient pathways will involve a range of actions appropriate to potentials for vulnerability/risk reduction at those scales (*high confidence*; *high agreement, medium evidence*). Although at a global scale both mitigation and adaptation are essential, relatively local scales in many developing regions have limited capacities to include mitigation in their climate-resilience strategies because they contribute very little to the causes of climate change. At all scales, however, actions are important to assure that effective risk management can be implemented and sustained. [20.2.3, 20.6.1]

Although outcomes from specific actions are often uncertain, strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve human livelihoods, social and economic well-being, and responsible environmental management (*high confidence*; *high agreement, medium evidence*). Actions at the present time will emphasize co-benefits and iterative learning, with risk management strategies and capacities refined continually on the bases of growing evidence, knowledge, and experience. [20.6.2]

Meanwhile, what is known about integrating climate change mitigation, climate change adaptation, and sustainable development is dwarfed by what is not known (*high confidence*; *high agreement, strong evidence*). Improving the base of knowledge about relationships and potentials for progress with climate resilience is a high priority, as a basis for adaptive learning and action. [20.7]

20.1. Introduction

Following summaries of *what we know* about climate change impacts, vulnerabilities, and prospects for adaptation (Chapter 18) and of *what we should be most worried about* (Chapter 19), this concluding topical chapter of the Working Group II Fifth Assessment Report summarizes what is currently known about options regarding *what to do* in responding to these risks and concerns.

In terms of "what to do" to minimize climate change and threats to development now and in the future, this chapter identifies and discusses climate-resilient pathways. Climate-resilient pathways are evolutionary processes for

managing change within complex systems in order to reduce disruptions and enhance opportunities. They are rooted in continuing, interactive processes of identifying vulnerabilities to climate change impacts; taking appropriate steps to reduce vulnerabilities in the context of development needs and resources, building capacity to increase the options available for vulnerability reduction and coping with unexpected threats; monitoring emerging climate parameters and their implications and the effectiveness of vulnerability reduction efforts; and revising risk reduction responses on the basis of continuing learning. This process may involve a combination of incremental changes and, as necessary, significant transformations (see sections 20.2.3.1 and 20.6.2; for related UNFCCC language, see Box 20-1). As such, climate-resilient pathways include two essential elements:

- Actions to reduce climate change and its impacts, including both mitigation and adaptation
- Actions to assure that effective risk management institutions, strategies, and choices will be identified, implemented, and sustained as an integrated part of development processes.

_____ START BOX 20-1 HERE _____

Box 20-1. UNFCCC Goals for Climate-Resilient Pathways

Climate resilient pathways are trajectories of combined mitigation and adaptation that are consistent with the aims of sustainable development and which do not traverse the threshold of "dangerous anthropogenic interference with the climate system" as specified in Article 2 of the Convention.

Article 2 of the United Nations Framework Convention on Climate Change presents the ultimate objective as the, '*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'* According to the Convention, the climate system must not be dangerous in order to "allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". Article 3.4 recognizes that "Parties have a right to, and should promote sustainable development." The Copenhagen Accord of 2009 states, "To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change."

The Cancun Agreements Decision 1/CP.16 confirms this with a view that "… recognizes … deep cuts in global greenhouse gas emissions are required according to science, and as documented in the Fourth Assessment Report of the IPCC, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2°C above preindustrial levels…consistent with science…[and] also recognizes the need to consider, in the context of the first review… strengthening the long-term global goal on the basis of the best available scientific knowledge.

The 2011 Conference of the Parties in a decision known as the Durban Platform increases the strength of the language in the decision 1/CP.17 to conclude, "… climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires to be urgently addressed … with a view to accelerating the reduction of global greenhouse gas emissions.... This decision was followed by the decisions adopted in Doha at the 18th Conference of the Parties that noted w*ith grave concern* the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2 °C or 1.5 °C above pre-industrial levels. As such, the current UNFCCC negotiations have adopted +2°C or 1.5 C as the desirable target upper limit and equated this with "dangerous" in Article 2.

_____ END BOX 20-1 HERE _____

In many cases, each of the two categories of responses has the potential to benefit the other as well, offering potentials for win-win kinds of integration, although mechanisms and institutions are needed to address cases where the two elements have negative effects on each other and to assure that positive synergies are realized. Because

climate change challenges are significant for many areas, systems, and populations, climate-resilient pathways will generally require transformations in order to assure sustainable development – beyond incremental approaches.

The chapter shows how climate-resilient pathways can recognize the relationship between mitigation, adaptation and sustainable development and invoke transformative actions to deliberately avoid dangerous climate change and its impacts. It examines the attributes and characteristics of pathways for sustainable development that are resilient to impacts of climate change, including potentials and possible limitations. In doing so, the chapter integrates a variety of complex issues in assessing climate-resilient pathways in a variety of regions at a variety of scales: sustainable development as the ultimate aim, mitigation as the way to keep climate change impacts moderate rather than extreme, adaptation as a response strategy to cope with impacts that cannot be (or are not) avoided, and development pathways as contexts that shape choices and actions.

The chapter is organized in six parts: climate change as a threat to sustainable development, assessing links between sustainable development and climate change as well as defining climate resilient pathways (20.2), contributions to resilience through climate change responses (20.3), contributions to resilience through sustainable development strategies and choices (20.4), determinants of resilience in the face of serious threats (20.5), challenges in moving toward climate-resilient pathways (20.6), and priority gaps in knowledge (20.7).

Several of the terms that are central to this chapter have been defined earlier in the Working Group 2 Fifth Assessment Report, including climate, adaptation, and mitigation. In addition, by "resilient" we mean a system's capacity to anticipate and reduce, cope with, and respond to and recover from disruptions (IPCC SREX, 2012). For literatures on "sustainable development," see section 20.2.1 below. A summary definition is development that achieves continuing improvements in human well-being and assures a sustainable relationship with a physical environment that is already under stress, reconciling tradeoffs among economic, environmental, and other social goals through institutional approaches that are equitable and participative in order themselves to be sustainable.

20.2. Climate Change as a Threat to Sustainable Development

Climate-resilient pathways bring together (a) sustainable development as the larger context for societies, regions, nations, and the global community with (b) climate change effects as threats to (and possibly opportunities for) sustainable development and responses to reduce those effects that would undermine future development and even offset already achieved gains.

20.2.1. Links between Sustainable Development and Climate Change

20.2.1.1. Objectives of Sustainable Development

Understandings of sustainable development have developed considerably, particularly over the past two decades, as the short- and long-term implications of climate change and extreme events have become better understood, although empirical evidence of progress with sustainable development is often elusive. The discussion of sustainable development in the IPCC process has evolved since the First Assessment Report, which focused on the technology and cost-effectiveness of mitigation activities, and the Second Assessment Report (SAR), which included issues related to equity and to environmental and social considerations. The Third Assessment Report (TAR) further broadened the treatment of sustainable development by addressing issues related to global sustainability, and the Fourth Assessment (AR4) included chapters on sustainable development in both WG II and III reports, with a focus on both climate-first and development-first literatures, although integration of the two working group perspectives remains a work in progress.

"Sustainable development" is a concept rooted in many decades of concerns about balance in the relationships between society and nature (e.g., Brown, 1981). These concerns grew during the 1960s and 1970s in connection with observations of a declining quality of the environment coupled with increasing needs for natural resources as human populations expand and energy-.and other input-intensive living standards rise. Early initiatives (particularly

in industrialized countries) focused the quality of water, air, management of hazardous materials and other individual attributes of the environment. In those decades, some of the outcomes from the initiatives included an array of regulations intended to manage and improve resource management, a movement toward recycling of consumable resources, and an emphasis on renewable energy as a substitute for energy production that consumed non-renewable fossil fuel resources (Frey and Linke, 2002).

The Brundtland Report defines sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The report recognizes that poverty is one of the main causes of environmental degradation and that equitable economic development is key to addressing environmental problems both in developing and developed region (Halsnaes et al., 2008; Lafferty and Meadowcroft, 2010). From a practical perspective, sustainable development has been "operationalized" through Agenda 21, which is a comprehensive plan of action adopted at the 1992 Earth Summit by more than 178 governments (Sitarz, 1994). In June 2012, participants in the "Rio+20" conference issued a statement urging countries to renew their commitment to sustainable development.

Although the existing global discourse and practice around sustainable development has helped to establish some commonly held principles, the concept itself remains elusive and contested (e.g., Hopwood, Mellow, and O'Brien, 2005; Jabareen, 2008). For example, sustainable development has been criticized as being vague and immeasurable; and its connections with continued economic growth have drawn suspicion from those who believe sustainable development is a strategy to slow or limit development in the developing world, those who think that current trends in consumption patterns are themselves non-sustainable (e.g., Robinson, 2004), and those who believe that current institutional controls and linkages are seriously counterproductive (Scrieciu et al., 2011; Barker, 2008; O'Hara, 2009). Whereas some authors equate sustainable development with equity and values through which climate policies can be implemented (see IPCC Working Group III: Chapter 4), in practice some national authorities interpret sustainable development as the goal of pursuing economic development through the models embraced in industrialized countries.

With time, two factors have become evident (Brown, 2011**;** Grist, 2008; Sanwal, 2012). First, development has the potential to fundamentally alter global environmental systems, including climates (IPCC, 2007); and second, the basic model of development continues to aspire to the fossil-fuel intensive systems in place in most industrialized countries – from food production, trade, transport, and household consumption. This model still largely define development processes in practice, adding to challenges in realizing "sustainable" development. Until these two factors are reconciled, it may be difficult to attain climate-resilient pathways in either industrialized or developing countries, with associated consequences (Marston, 2012; Grist, 2008**).**

One way that sustainable development pathways can contribute to climate resilience is by pursuing consumption patterns that assure social and economic development without being wasteful of natural resources and the environment. It is possible that, rather than letting consumption be driven by familiar patterns of resource demands, the desired objectives of consumption might be met in ways that require lesser quantities of resources and produce lesser quantities of environmental emissions (Kates, 2000; also see Leiserowitz, Kates, and Parris, 2005).

Overall, development is a means to social and economic ends, not (usually) an end in itself; the objective is to develop in order to increase the abundance and reliability of services that are important to well-being, such as food, shelter, productivity, and enjoyment (Sen, 1999; Morgan and Farsides, 2009). For example, we do not develop improved energy systems because we want to consume kilowatts of electricity for their own sake; we consume them because they deliver comfort, convenience, and other qualities that we desire (Von Bernard and Gorbaran, 2010). Within the context of a changing climate, continued use and unlimited expansion of the limited resources of this planet does not seem consistent either sustainable development or climate resilient development (Ehrenfeld, 2008; Gilbert, 2006; also see Victor, 2008 and Victor and Rosenbluth, 2007).

There is a growing debate about economic growth and material consumption. Sustainable development is all about lifestyles, ways of life, and human well-being, which in turn are associated with – but not necessarily defined by -- the consumption of natural and material resources (e.g., Easterlin, 1974 and 2001; Adger, 2010; also see IPCC Working Group III: Chapter 4). One point of view in social research suggests that ever-increasing material

consumption does not necessarily bring greater happiness or satisfaction or material comfort (DeLeire and Kalil, 2010; Cafaro, 2010; Huesemann, 2006). On the other hand, in many cases growth in consumption, especially among populations with incomes rising from low levels, is greatly beneficial (Clark, Frijters, and Shields, 2008; and Deaton, 2008). Measuring human well-being as a dimension of sustainable development that is not entirely captured by monetary income and level of consumption remains both a challenge and a need (Dolan and White, 2007; Fleurbaey, 2009).

20.2.1.2. Risks and Threats Posed by Climate Change, Interacting with Other Factors and Driving Forces

As the extent of implications of climate change become better-understood (Chapter 18) and as particular reasons for concern have begun to come into focus (Chapter 19), climate change has been increasingly seen as an issue for sustainable development – with the potential either to aid or impede its successful implementation (e.g., Halsnaes et al., 2008; Munasinghe, 2010). The links between sustainable development and climate adaptation and mitigation are cross-cutting and complex. First, the effects of climate change may derail current sustainable development policy and potentially offset already achieved gains (World Bank, 2010; also see Boxes 20-2 and 20-3). For example, effects of climate change on key ecological resources and systems can jeopardize sustainable development in systems closely linked to natural capital. Second, mitigation has the potential to keep these threats at a moderate rather than extreme level, and adaptation will enhance the ability of different systems to cope with the remaining impacts, therefore modulating negative effects on sustainable development (IPCC, 2007). Third, many of the conditions that define vulnerability to climate impact and the ability to respond to them are firmly rooted in development processes (e.g., structural deficits and available assets and entitlements) (Brooks et al., 2005; Lemos et al., forthcoming; Chapter 15). Fourth, sustainable development intersects with many of the drivers of climate change, especially regarding energy production and consumption and the ability to mitigate emissions (IPCC SRREN, 2012; also see Chapter 9). Fifth, because several of the desirable conditions for successful mitigation and adaptation may overlap with those of sustainable development (e.g. implementation of no-regrets interventions, equitable distribution of resources, increased adaptive capacity and livelihood capitals), systems where sustainable development has been prioritized may provide a more conducive context for the implementation of successful mitigation and adaptation (Brown, 2011). Finally, climate mitigation and adaptation, if planned and integrated well, have the potential to create opportunities to further foster sustainable development (see section 20.3.3 below). Under the threat of climate change, sustainable development depends on changes in social awareness and values that lead to innovative actions and practices, including increased attention to both disaster risk management and climate change adaptation in anticipation of (and in response to) changes in climate extremes (IPCC SREX, 2012). Understanding how to enhance positive feedbacks between mitigation, adaptation, and sustainable development while minimizing negative feedbacks is an essential part of planning for and pursuing climate-resilient pathways. In the following paragraphs, we discuss these links in light of empirical research and specific examples (Boxes 20-2 and 20-3). While some of the links described above have been contemplated in the scholarly literature, there remain considerable gaps on our knowledge base to inform climate-resilient pathways.

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Box 20-2. Key Reasons for Concern about Climate Change Effects on Sustainable Development

Chapter 19 of this report identifies key vulnerabilities to climate change that might affect sustainable development. Recognizing that the distribution of such impacts can be uneven and variable across space, time, and a number of dimensions of vulnerability, the major concerns about effects on sustainable development include:

- Risks to glaciers and the human systems supported by their meltwater
- Risks from extreme weather events
- Deterioration of regional food security
- Increased water stress in some areas
- Impacts on human health
- Losses of endangered species and biodiversity.

Cross-cutting concerns include aggregate impacts, the distribution of impacts, and large-scale singular events associated with system thresholds and irreversible change.

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Box 20-3. Connecting Representative Concentration Pathways (RCPs) with Shared Socioeconomic Pathways (SSPs)

The climate change science community has developed a new set of visions of a range of climate futures, called "Representative Concentration Pathways" or RCPs, intended to replace the rich families of SRES scenarios (IPCC, 2000) that were used extensively by IPCC and others for a decade. As reported in Moss et al., 2010, the RCPs include four representative pathways to illustrate the range of possible climate futures, defined in terms of approximate radiative forcing levels. These scenarios represent a broad range of potential climate outcomes, both over the near term (to 2035) and longer term (2100 and beyond).

To accompany these RCPs and provide context for assessing impacts of such futures, the climate change science community is also developing a set of representative socioeconomic futures, reflecting different pathways of economic intensity, capacity for societal problem-solving, and other dimensions of socioeconomic futures, called Shared Socioeconomic Pathways (SSPs), each defined by a storyline and supported by qualitative and quantitative characterizations (Kriegler et al., 2012; Ebi et al., forthcoming; O'Neill et al., forthcoming). In principle, it will be possible to compare socioeconomic conditions (SSPs) with climate forcings (RCPs) to evaluate such issues as differences in needs and challenges for mitigation or the feasibility of adaptation associated with different contexts regarding driving forces (see section 20.6.1).

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The relationship between climatic change and development policy has often been theorized as essentially twofold. On the one hand, climate change will affect development policy as needs to respond to negative, and perhaps positive, impacts arise (Schipper, 2007; Burton et al., 2002; Halsnaes and Verhagen, 2007). On the other hand, development policy critically shapes carbon emission paths, the ability to develop sustainable adaptation and mitigation options, and to build overall adaptive capacity (Bizikova, Robinson, and Cohen, 2007; Garg et al., 2009; Metz and Kok, 2008; Lemos, et al., 2007). Because of the recognized relationship between development and climate change drivers and responses, some authors have called for a "political economy of climate change" that takes into consideration ideas, power, and resources at different scales from the local to the global (e.g., Tanner and Allouche, 2011).

Enhancing resilience to respond to effects of climate change includes adopting good development practices that are consonant with building sustainable livelihoods and, in some cases, challenging current models of development (Boyd et al., 2008; McSweeny and Coomes, 2011). Moreover, promoting development pathways that are both equitable and sustainable is also a key to addressing climate change (Wilbanks, 2003; Nelson et al., 2007). Yet, whereas climate change impacts are often strongly correlated with threats to sustainability, the debate on climate change has tended to run separately from the wider sustainability discourse (Cohen et al., 1998; IPCC, 2001). Integrating sustainable development and overall climate change policy can be all the more relevant if "cross-linkages between poverty, the use of natural capital and environmental degradation" are recognized (Veeman and Politylo, 2003: 317; also see Matthew and Hammill, 2009). Especially in less developed countries/regions, the relationship between vulnerability to climate impacts and development is often inclusive and mutually dependent as such realities as low per capita income and inequitable distribution of resources; lack of education, health care, and safety; and weak institutions, unequal power relations and weak democracy fundamentally shape sensitivity, exposure and adaptive capacity to climate impact – along with other factors influencing risks (Garg et al., 2009; McSweeny and Coomes, 2011; Adger et al., 2003; Kates, 2000). In these regions, reducing risks that affect resource-dependent communities is increasingly viewed as a necessary,but insufficient way to tackle the myriad of problems associated with climate change impacts (Jerneck and Olsson, 2008). Building the capacity of individuals,

communities and governance systems to adapt to climate impacts is both a function of dealing with developmental deficits (e.g. poverty alleviation, reducing risks related to famine and food insecurity, enabling/implementing public health and mass education and literacy programs) and of improving risk management (e.g. alert systems, disaster relief, crop insurance, climate forecasts) (Mirza, 2003; Schipper and Pelling, 2006). Hence, especially in less developed regions, it is important not only to understand the relative importance of different kinds of interventions (climate and non-climate) in building adaptive capacity but also the potential positive and negative synergies between them (Lemos et al., forthcoming).

While research increasingly highlights the intersection between vulnerability, adaptive capacity and developmental structural deficits, however, there is also growing recognition that the intractability of many of these problems may inhibit the development of climate-resilient pathways. For example, research by Wolf et al. (2009) on climate change responses in western Canada shows that self-efficacy and ecological citizenship play an important role in the identification and implementation of sustainable responses to water scarcity. In contrast, inequitable distribution of power among those affected by climate impact can suppress innovative decisions about the future by limiting their participation in designing solutions. Research focusing on disaster response in Mexico shows that alienation of individuals is instrumental to creating a compliant citizenry, and that resilience is undermined by a limited breadth of learning and experimentation, centralized power, and limited economic diversity (Pelling and Navarrete, 2011). In Northeast Brazil, the fact that local traditional politics relied on client-list relationships with drought-affected households to maintain power suggests that there was little incentive for policies that dramatically decreased their level of vulnerability (Tompkins, Lemos, and Boyd, 2008). Omolo (2010) argues that in the northwestern Kenya, in pastoralist societies of Turkana, in spite of increasing numbers of women headed households, participation of women in key decisions such as investment, resource allocation, and planning on where to move or settle in the aftermath of drought and floods is still quite low. A serious concern is that our inability to readily address these kinds of structural problems may limit options for future generations of marginalized social groups to be active agents of a climate resilient future. In this sense, it is critical to understand how existing path-dependent trajectories (e.g., socio-technical, behavioral, institutional) that form the contextual basis for climate change action at different scales (Burch, 2010) may inhibit (or help) the realization of future climate resilient pathways.

A number of studies recognize that not every possible response to climate change is consistent with sustainable development, in that some strategies and actions may have negative impacts on the well-being of others and future generations (Eriksen et al., 2011; Gardiner et al., 2010). For example, some mitigation measures, such as changing the composition of the atmosphere through geoengineering, could influence large-scale weather systems and create potentially dangerous conditions or new problems for many others (Gardiner et al., 2010, Carlin, 2007; Brovkin et al., 2009; de Sherbinin et al., 2011; also see Box 20-6). Likewise, some adaptation measures, such as using more surface water or groundwater for irrigation, may have negative effects on other users and more rapidly deplete scarce natural resources that could come under increasing pressure with climate change (Eriksen et al., 2011). The consequences of responses to climate change, whether related to mitigation or adaptation, can negatively influence future vulnerability, unless they are linked to the wider context of sustainable development (Bizikova et al., 2010). Here, the role of values in responding to climate change becomes important from a variety of perspectives, including intergenerational, particularly when those currently in positions of power and authority assume that their prioritized values will be shared by future generations (O'Brien, 2009). Acknowledging the importance of intergenerational equity, it has been argued that participatory processes and 'deliberative democracy' can include the concerns, values and perceptions of a wide range of stakeholders, raising some of the ethical impacts attached to climate related risks (Backstrand, 2003; also see Deere-Birebeck, 2009). Such an approach could have a bearing on the way risks are assessed and addressed at the science-policy interface, with significant implications for sustainable development. In light of the complex interactions among climate change responses and sustainable development, there is a need for more holistic responses that place human well-being and security at the forefront, while building on existing strengths and capacities (Tompkins and Adger, 2004; O'Brien et al., 2010). This entails integrating multiple objectives and policy goals and the way to assess them to promote sustainable responses to climate change that contribute to resilience (Meadowcroft, 2000; Tompkins and Adger, 2004; Pinter et al., 2011).

A reality in many countries may be that development – which seeks to increase economic wealth – can enhance the capacity to adapt while at the same time adding to greenhouse gas emissions. Yet, the World Development Report 2010 suggests that climate change responses have the potential to contribute to sustainable development as, for

example, in the case of financial assistance with transition to low-carbon growth paths (World Bank, 2010) or in the case of mitigation policies that could increase income and/or enhance the quality of growth in vulnerable groups such as REDD (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries). And while vulnerable sectors such as agriculture give us particular reasons for concern (see Box 20-4), they may offer opportunities in some instances to reduce climate related risks and threats by integrating both adaptation and mitigation strategies as a lever for reducing poverty and promoting climate resilient pathways. Particularly necessary is addressing institutional and social capacities for responding to both climate change impacts and mitigation responses. For example, Chhatre and Agrawal (2009) show that climate change mitigation can benefit livelihoods if ownership of forest commons is transferred to local communities. These kinds of possible implications of climate change connect with drivers of sustainable development, and in turn social and economic dimensions of development affect the likelihood of effective responses to climate change risks (see Box 20-4). Moreover, some interventions related to climate change responses aim to combine goals of sustainable development, climate change adaptation, and climate change mitigation into "triple win" approaches that highlight overlaps between these goals. Examples include mechanisms such as the Clean Development Mechanism (CDM) and Joint Implementation (JI) (e.g., Millar, Stephenson, and Stephens, 2007), which seek to offset carbon emissions, build adaptive capacities of local communities, and provide sustainable development dividends despite mixed results in terms of accomplishing these goals in practice (Corbera and Brown, 2008). Specifically in the case of the CDM, robust empirical research shows that while the goal of offsetting carbon emissions has been relatively successful, generating sustainable development dividend has been difficult. For example, after examining sixteen existing CDM projects around the world, Sutter and Parreno (2007) found that whereas they are likely to meet 72% of their emissions reduction goals, less than 1% iarelikely contribute significantly to sustainable development in the host country. Furthermore, their research suggests that there might be an actual tradeoff between the goals of efficient generation of carbon emissions certificates (CERs) and the broader generation of the sustainable development dividend (also see Winkelman and Moore, 2011). Because relationships among the three goals can lead to both positive and negative consequences, it is important to unravel conditions that lead to desirable outcomes (Chhartre and Agrawal, 2009) (see section 20.3.3). Moreover, the fact that currently available institutional arrangements that combine mitigation and sustainable development such as the CDM are not achieving their win-win goals indicates the need for rapidly developing means for evaluating, changing and improving what is not working (Pressman and Wildavsky, 1984).

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Box 20-4. Case Studies from China

Water-saving irrigation has enhanced the climate change adaptation capacity, improved ecosystem services, and promoted regional sustainable development in China:

- ***Water-Saving Irrigation Measures in Cropland Adaptation to Climate Change***
  Water-saving irrigation is one effective measure to deal with the water scarcity and food security issues caused by climate change (Hanjra and Qureshi, 2010; Tejero et al., 2011). Given an increase in non-agricultural water consumption, China's agriculture could be faced with a severe shortage of water resources (Xiong et al., 2010). Through water-saving irrigation practices, water saved from 2007-2009 added up to 30.7-34.92 Gm^3 for each year, which accounted for 5.6%~11.8% of the national total water consumption. For example in 2009, according to current agricultural water consumption conditions, the saved water enabled expansions of the irrigated cropland by 3.80-7.80 Mhm^2 and increase grain production by 14.68-30.15 Mt, enough to meet one year grain needs of 73-151 million people (Zou et al., 2012) (Table 20-1). Besides, the performance of water saving irrigation from 2007-2009 saved about 9.59-20.85 Mt of standard coal and reduced 21.83-47.48Mt CO_2 emissions, which not only alleviated electric and diesel pressure in rural area but also reduced agricultural GHG emissions Therefore, water-saving irrigation has had a positive effecct in dealing with climate change and sustainable development (Zou et al., 2012).
  [INSERT TABLE 20-1 HERE
  Table 20-1: Effectiveness of water-saving irrigation dealing with climate change (Zou et al., 2012).]
- ***Water-Saving Irrigation Measures in Alpine Grassland for Adapting to Climate Change***
  Northern Tibet is the headwater region for the Yangtze, Nu (Salween River), Lancang (Mekong River), and numerous other rivers and high mountain lakes (Gao et al., 2009). Sustaining environmental conditions in the region is of vital importance not only for Tibet but also for China as a whole. Being a fragile ecosystem,

the alpine grassland ecosystem in Northern Tibet is extremely sensitive to climate change and human activity. In recent years, the rise in precipitation and temperature results has led to the melting of glaciers and expansion of inland high mountain lakes, contributing to alpine grassland degradation in Northern Tibet (Gao et al., 2010). Among many grassland protection measures, alpine grassland water-saving irrigation measures could be effective in redistributing and making full use of increased precipitation and lake water in the dry period, which would reduce the negative effects of climate change and make full use of favorable conditions (Editorial Board of National Climate Change Assessment, 2011). A three-year demonstration of alpine grassland water-saving irrigation measures showed that alpine grassland yield nearly doubled (Figure 20-1b) while the plant species increased from 19 to 29, helping to protect and restore the alpine grassland ecosystem and ecosystem services and to promote regional socio-economic sustainable development in Northern Tibet (Gao et al., 2012).

[INSERT FIGURE 20-1 HERE

Figure 20-1: The demonstration of alpine grassland water-saving irrigation measures for adaptation to climate change in Northern Tibet.]

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Given these connections, there is growing consensus in the literature about a need to integrate development and climate policies; however, the means to achieve this integration differ. One option is the "development first" approach which suggests that the incorporation of climate concerns within prevalent development interventions is the best option, since development is usually the highest priority (Kok et al., 2008). In this approach, governments take into consideration tradeoffs between different dimensions of sustainability and look for climate-inclusive policy options that offer positive synergies with development, aiming at both low greenhouse gas emissions and low vulnerabilities to climate impacts (if their development paradigms are flexible enough to expand in such a way). Lessons from this literature also emphasize the contextual and place-based character of these processes and the need to understand opportunities and constraints relative to local, national, and global priorities (Wilbanks and Sathaye, 2007). Factors constraining the 'mainstreaming' of climate adaptation into development include discrepancies between immediate development goals and future climate change scenarios, especially in less developed regions and emerging economies. They also include a growing disconnect between donors' goals and developing countries' own development agendas (Agrawala, 2004; Klein, Schipper, and Desai, 2005), potentially inhibiting the development of robust local institutions that can effectively integrate or mainstream climate change policy into to their development priorities. Many developing countries lack technical assistance and capacity development to support their climate change agendas and to identify and manage risks. Often, programs tend to be poorly coordinated, fragmented, and bureaucratic, thus accentuating the isolation that vulnerable communities feel with regard to access to such programs, and even where programs are reasonably well-coordinated bureaucratic complexities can cause communities to be overlooked (Chukwumerije and Schroeder, 2009). Other factors -- such as lack of financial and human resources, unclear distribution of costs and benefits, fragmented management, mismatches in scale of governance and implementation, lack and unequal distribution of climate information, and trade-offs with other priorities – may also limit the smooth mainstreaming of climate adaptation action into development (Agrawala and van Aalst, 2008; Bizikova et al., 2007; Eakin and Lemos, 2006; Kok et al., 2008; Metz and Kok, 2008). Finally, empirical evidence suggests that the relationship between development variables and climate change responses can be a mixture of positives and negatives, if development variables are not managed well (Garg et al., 2009). For example, in a study of the relationship between malaria incidence, development and climate variables in India, Garg et al. (2009) found that while some development interventions such as increased availability of irrigation canals and dams can negatively affect the incidence of malaria and water-borne diseases, others such as higher per capita income can reduce negative health impacts of climate change significantly – although the distribution of benefits can differ between types of interventions (also see Campbell-Landrum and Woodruff, 2006). Understanding how development variables intersect with climate responses is especially important because governments and other actors rarely make decisions in isolation; rather they respond to multiple stressors both in rural and urban environments (Agrawal, 2008; Eakin, 2005; Wilbanks and Kates, 2010). Moreover, some evidence suggests that, in practice, decision-makers (from heads of households to policy-makers) often do not place climate change at the top of their priority list of critical issues to address (Garg, Shukla, and Kapshe, 2007; Kok et al., 2008), although in some regions (e.g., in Africa) special climate-oriented bureaus are being placed strategically in the offices of government leaders. For instance, in Kenya and Tanzania climate change coordination units have been created in high-level

scales of government. These institutional arrangements constitute a growing realization of the strategic place that climate change issues occupy in some countries in Africa. The growing importance of climatic change in shaping social and governmental policy agendas has resulted in many examples of specific interventions to respond to climate change both in developed and developing regions (Ayers and Huq, 2009; Burch, 2010; Dang, Michaelowa, and Tuan, 2003), for reasons that appear to vary widely.

20.2.3. Climate-Resilient Pathways

20.2.3.1. Framing Climate-Resilient Pathways

Climate-resilient pathways connect climate change consequences with development pathways (see IPCC Working Group III: Chapter 4). They are evolutionary processes for managing change within complex systems. Pathways follow a direction; this may be toward unintended consequences of previous actions (e.g., global temperature increases of 2°C or more) or toward intended goals or visions (e.g., sustainable development). Unintended consequences are common in complex systems, where feedbacks, teleconnections, cross-scale linkages, and thresholds, and nonlinearities can result in non-linear effects that were not anticipated (Folke et al., 2002; Scheffer et al., 2009; Lenton, 2011a). Climate-resilient pathways reflect an intended goal that takes into account the knowledge that increasing atmospheric concentrations of greenhouse gas will have long-term implications for sustainable development (IPCC Working Group I). Reflecting evolutionary uncertainties, they are rooted in iterative responses that involve identifying vulnerabilities to climate change impacts; assessing opportunities for reducing risks; and taking actions that are consistent with the goals of sustainable development.

The pursuit of climate-resilient pathways may involve a combination of incremental changes and transformative responses that take into account: 1) current and anticipated changes in both climate averages and extremes; 2) the dynamic development context that influences social vulnerability, risk perception, conflict resolution, and resilience; and 3) recognition of human agency and capacity to influence the future. This last point is significant, as humans have the capacity to manage risk and to decrease vulnerability through both mitigation and adaptation, as well as through choices of development goals and strategies (IPCC SREX, 2012). Given the non-linear impacts associated with increasing global temperatures, the threats to sustainable development are likely to become greater over time (Wilbanks et al., 2007; Stafford et al., 2010). This may require transformational adaptations, i.e., responses that change the nature, composition, and/or location of threatened systems in order to maintain the potential for sustainable development (Smit and Wandel, 2006; Stringer et al., 2009; NRC, 2010a; Pelling, 2010; IPCC SREX, 2012: see section 20.5).

Climate resilient pathways call for decisions and actions that take into account both short- and long-term time horizons. Near-term responses may emphasize climate change mitigation and relatively low-cost adaptations that present development co-benefits (Van Aalst, Cannon, and Burton, 2008; NRC, 2010a). Anticipating long-term responses calls for monitoring emerging impacts and risks combined with adaptive management, learning, leadership and contingency planning (NRC, 2010a; IPCC SREX, 2012).

20.2.3.2. Elements of Climate-Resilient Pathways

As climate change continues on its current path toward relatively significant impacts (NRC, 2010b), climate-resilient pathways will become increasingly challenging, requiring explicit attention to responses in virtually all regions, sectors, and systems in order to avoid disruptions of development processes. Climate-resilient pathways include two overarching attributes: (1) actions in order to reduce climate change and its impacts, including both mitigation and adaptation, and (2) actions to assure that effective risk management institutions, strategies, and choices can be identified, implemented, and sustained as an integrated part of development processes (Edenhofer et al., 2012). Box 20-5 lists a number of attributes of climate-resilient pathways categorized into awareness and capacity, resources and practices. Each of the items is amenable to strategy development in appropriate national, regional, and local contexts. For example, in many cases effective response to extreme events is likely to benefit both from iterative problem-solving and bottom-up engagement in risk management, and from human development

to enhance capacities for risk management and adaptive behavior (Tompkins, Lemos, and Boyd, 2008). Folke (2006) characterizes resilience as a process of innovation and development. Pathways should therefore be continuously moving toward a more adapted and less vulnerable state; in some instances, there may be stages of slow development followed by periods where progress increases speed. Further, the nonlinearity or randomness of climate impacts necessitates a system that allows for the flexibility to adapt to unexpected and even extreme events (Hollings, 1973). This is especially true in light of political, economic or resource constraints, where pathways at the local level will need to not only be flexible but also practical and feasible in both the short term and long term. One of the most challenging aspects of climate-resilient pathways is that they exist in distinctive local contexts, where they are shaped by external linkages that connect them across geographic scales and time. For example, resilience cannot be achieved in a few privileged places if it is not achieved in others, because instabilities in adversely impacted situations will spill over to other situations through such effects as resource supply constraints, conflict, migration, or disease transmission (Wilbanks, 2009; IPCC SREX, 2012: Chapter 7).

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Box 20-5. Elements of Climate-Resilient Pathways for Sustainable Development

Awareness and capacity

- A high level of social awareness of climate change risks
- A demonstrated commitment to contribute appropriately to reducing global net GHG emissions, integrated with national development strategies
- Institutional change for more effective resource management through collective action
- Human capital development to improve risk management and adaptive capacities
- Leadership for sustainability that effectively responds to complex challenges

Resources

- Access to scientific and technological expertise and options for problem-solving, including effective mechanisms for providing climate information and services
- Access to financing for appropriate climate change response strategies and actions
- Information linkages in order to learn from experiences of others with mitigation and adaptation

Practices

- Continuing, institutionalized vulnerability assessments and risk management strategy development and refinement based on emerging information and experience
- Monitoring of emerging climate change effects and contingency planning for possible significant impacts and needs for transformational responses
- Policy, regulatory, and legal frameworks that encourage and support distributed voluntary actions for climate change risk management
- Effective programs to assist the most vulnerable populations and systems in coping with impacts of climate change

_____ END BOX 20-5 HERE _____

Climate resilient pathways are in fact a process, not an outcome (Manyena, 2006), involving both incremental and transformational changes. The pathways therefore need to be built on a foundation of constantly advancing knowledge, where information is adjusted based on changing scientific knowledge climate parameters and altering social, economic and natural resource situations (Berkes, 2007). While some measures will be reactive, the main elements of a pathway are intentional and proactive; anticipating future change and developing appropriate plans and responses. Although payoffs from specific long-term pathways may be unknown, strategies and actions can be pursued now that will contribute significantly to moving toward climate-resilient pathways while helping to improve human livelihoods, social and economic well-being, and responsible environmental management (section 20.6.2).

20.3. Contributions to Resilience through Climate Change Responses

Climate change responses include mitigation, adaptation, and integrated mitigation and adaptation strategies. Related to these responses but generally considered a separate response issue is "geoengineering" (Box 20-6).

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Box 20-6. Considering Geoengineering Responses

To the extent that climate change mitigation is not fully successful in moderating the rate of increase in GHG emissions, and if climate change adaptation is not successful in coping with the resulting impacts without socially unacceptable pain and distress, policymakers may be faced with demands to find further ways to reduce climate change and its effects.

Such options include expansions of mitigation and/or adaptation to include geoengineering: intentional large-scale interventions in the earth system either to reduce the sun's radiation that reaches the surface of the earth or to increase the uptake of carbon dioxide from the atmosphere. An example of the former is to inject sulfates into the stratosphere. Examples of the latter include facilities to scrub carbon dioxide from the air and chemical interventions to increase uptakes by oceans, soil, or biomass (UK Royal Society, 2009; IPCC Working Group III: Chapter 6).

Discussions of geoengineering have only recently become an active area of discourse in science, despite a longer history of efforts to modify climate (Schneider, 1996, 2009; Keith, 2000). Many of the possible options are known to be technically feasible, but their side-effects are exceedingly poorly understood (NRC, 2010b; MacCracken, 2011; Vaughan and Linten, 2011). For example, interventions in the atmosphere might not be unacceptably expensive, but they might affect the behavior of such earth system processes as the Asian monsoons (Robock et al., 2008; Brovkin et al., 2009). Interventions to increase uptakes, such as scrubbing carbon dioxide from the earth's atmosphere, might be socially acceptable but economically very expensive. Moreover, it is possible that optimism about geoengineering options might invite complacency regarding mitigation efforts (Barrett, 2008).

In any case, implications for sustainable development are largely unknown. Even though some advocates argue that geoengineering is needed now in order to avoid irreversible impact such as the loss of ocean corals, the more general view is that this is a research priority rather than current decision-making option (NRC, 2010b). The challenge is to understand what geoengineering options would do to moderate global climate change – and also to understand what their ancillary effects might be – so that, if policymakers find some decades from now that social responses to climate change have not been sufficient to avoid severe disruptions and, as a result, there is a need to consider rather dramatic technology alternatives, our understanding of potential costs and benefits for sustainable development is far better than it is now. Some observers propose that research efforts should include limited experiments with geoengineering options, but agreement has not been reached about criteria for determining what experiments are appropriate (e.g., Blackstock and Long, 2010).

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20.3.1. Mitigation

In IPCC's assessment reports, mitigation is the subject of Working Group III, to which the reader is referred for comprehensive information about options and strategies for reducing GHG emissions and increasing GHG uptakes by the earth system. For this chapter, the issue is how climate change mitigation relates to sustainable development, which was addressed by Chapter 12 of Working Group III's Fourth Assessment Report (IPCC 2007) and is also the focus of Chapter 4 of its Fifth Assessment Report, including attention of equity issues.

In general terms, mitigation is recognized to be important for sustainable development in two ways (Riahi, 2000). First, it reduces the rate and magnitude of climate change, which reduces climate-related stresses on sustainable development, including effects of climate extremes and extreme events (IPCC SREX, 2012). For example, in 2009

many smaller developing nations argued at UNFCCC COP 15 that stabilizing the global atmospheric concentration of carbon dioxide at 450 parts per million (ppm), projected to result in approximately a 2ºC increase in global mean temperature, would lead to unacceptable impacts on their prospects for sustainable development. Although the 450 ppm target appeared to be favored by many larger countries, some low-lying island nations would cease to exist in the face of the eventual sea-level rise that could result from that temperature increase. For these countries, any concentration level above 350 ppm (projected to result in approximately a 1.5ºC increase) was considered unacceptable given the risks (Liverman and Billett, 2010). In this sense, mitigation is a critically important part of climate change risk management (Washington et al., 2009; Lenton, 2011b; Peters et al., 2013). Second, trajectories for technological and institutional change in order to reduce net GHG emissions interact with development pathways. In some cases, strategies to promote low-carbon growth (e.g., Table 20-2) may be congruent with sustainable development in urban settings, such as green growth strategies that reduce local and regional air pollution, enhancing prospects for multi-level governance and integrated management of resources, and encouraging broader participation in development processes (Seto et al., 2010; Lebel, 2005). In other cases, such effects as higher energy prices associated with transitions from fossil fuels to renewable energy sources have the potential to have adverse effects on local and regional economic and social development (IPCC SRREN, 2012: Chapter 9). The challenge for climate-resilient pathways is to identify and implement mixes of technological and governance options that reduce net carbon emissions and at the same time support sustainable economic and social growth in a context where rising demands need to be combined with technology transitions without disrupting the development process. For example, such strategies as increasing carbon uptakes in the soil through better agricultural management practices – which can reduce net emissions – can improve soil water storage capacity and also reduce the workload of women, and practices such as conservation tillage can also increase water retention in drought conditions and help to sequester carbon in soils **(**Halsnaes et al., 2008**).**

However, mitigation and development also interact in a third way in that different groups and countries' ability to implement mitigation critically depends on their 'mitigative capacity' (Yohe, 2001): their "ability to reduce anthropogenic greenhouse gas emissions or enhance natural sinks" or the "skills, competencies, fitness, and proficiencies that a country has attained which can contribute to GHG emissions mitigation" (Winkler et al., 2007). Here, many of the determinants of mitigative capacity are fundamentally shaped by different countries' level of development, including their current level of emissions, their stock of human, financial and technological capital, such as the ability to pay for mitigation; the magnitude and cost of available abatement opportunities; the regulatory effectiveness and market rules; the education and skills base; the suite of mitigation technologies available; the ability to absorb new technologies, and the level of infrastructure development (see Box 20-3).

[INSERT TABLE 20-2 HERE
Table 20-1: Examples of national plans for low carbon growth (Araya, 2010).

20.3.2. Adaptation

Adaptation is the subject of four chapters of this Working Group II Fifth Assessment Report (14-17), to which the reader is referred for comprehensive descriptions of concepts, options, strategies, and examples of adaptation practices. For this section, we focus on the intersection between adaptation and sustainable development.

Overall, adaptation is linked to sustainable development in several ways. First, the ability of individuals, communities and governance systems to adapt to climate change impact is predicated on a number of capacities that enable the design and implementation of different types of intervention to prepare and respond to climate impact (Wilbanks et al., 2007). Globally and nationally, many of these determinants of adaptive capacity (e.g. human capital, information and technology, material resources and infrastructure, organization and social capital, political capital, wealth and financial capital, institutions and entitlements) (Smit and Pilifozofa, 2001; Yohe and Tol, 2002; Eakin and Lemos, 2006) significantly overlap with indicators of development. However, building these capacities both in developed and less developed regions has implications to sustainable development in terms of increasing the consumption of materials and potential negative effects on ecosystems (e.g. building of new infrastructure and increasing consumption).

Second, building adaptive capacity may critically contribute to the improvement of the well-being of both social and ecological systems by bettering livelihoods and reducing pressure on the environment, especially in less developed regions (see section 20.40.3). Regarding social systems, it is important to consider not only the factors that enable the building of different capacities (e.g. institutions and governance) but also how to guarantee that those who need it the most have access to them (Gupta et al., 2010; Nelson et al., 2007). It is also vital to understand how different capacities influence each other (positively and negatively) (Lemos et al., forthcoming) and how they may affect the long-term resilience of social-ecological systems (Adger et al., 2011; Box 20-5 illustrates the relationship between building technology and infrastructure capacities and long-term resilience and sustainability of agricultural social-ecological systems in China). Indeed, adaptation can be vitally important in reducing stresses on development processes, especially in vulnerable areas where it can help to promote and support sustainable development. For example, where adaptation planning stimulates participatory social processes, including equity and legitimacy discussions regarding different adaptation options, it can encourage communities to think more clearly about broader sustainable development goals and pathways (NRC, 2010a).

Third, given recent trends in GHG emissions and projections of climate futures that suggest impacts of climate change will be serious and widespread (e.g., Auerswald, Konrad, and Thum, 2011; Smith et al., 2011), adaptation may require considering transformational changes, in which potentially impacted systems move to fundamentally new patterns, dynamics, and/or locations (Schipper, 2007; Kates, Travis, and Wilbanks, 2012; Park et al,, 2012; Marshall et al., 2012). Desirable adaptation strategies may vary according to climate change threat, location, impacted system, the geographical scale of attention, and the time frame of strategic risk management planning (Heltberg, Siegel, and Jorgensen, 2009; Thomalla et al., 2006; NRC, 2010a). It is important that transformational adaptation policy at different scales takes into consideration the goals of sustainable development both by fostering positive synergies and by avoiding negative feedbacks between them, especially because some adaptation options might lead to inequitable and unsustainable outcomes (Thomas and Twyman, 2005; Eriksen et al., 2011; Eriksen and Brown, 2011) (for a more detailed discussion see sections 20.3.3 and 20.4.4). Moreover, adaptation at one scale may negatively affect vulnerability in another. For example, in Vietnam, policies for forestry protection and the construction of electric dams while benefiting low land areas (by regulating flooding) have critically constrained the access to land and forest products to mountain populations, decreasing their adaptive capacity (Beckman, 2011).

Indeed, adaptation pathways can foster food and water security, human health, and air and water quality and natural resource management, while promoting gender equality and other desirable outcomes. However, creating the conditions for the emergence of such outcomes will require better integration between the goals of adaptation and sustainable development at all scales. By selecting environmentally friendly materials; promoting energy, water and other resource conservation; promoting re-use and recycling; minimizing waste generation; protecting habitat and addressing needs of marginalized groups (Bizikova et al., 2007; Seto et al., 2010), adaptation can contribute to win-win or even triple win options that can support a diverse array of development goals (see section 20.3.3).

20.3.3. Integrating Climate Change Adaptation and Mitigation for Sustainable Risk Management

Recent research suggests that mitigation and adaptation are likely to be more effective when they are designed and implemented in the context of other interventions within the broader context of sustainability and resilience (Wilbanks and Kates, 2010; Asian Development Bank, 2012). Moreover, studies focusing on the intersection between sustainable development and climate policy point out that integration between the two is a desirable although complex path (Halsnaes et al., 2008; Wilson and McDaniels, 2007; Ayers and Huq, 2009; Beg et al., 2002). Wilson and McDaniels (345) suggest three reasons to integrate across adaptation, mitigation and sustainable development: (1) many dimensions of the *values* that are important for decision-making are common to all three decision contexts; (2) impacts from any one of the three decision contexts may have important *consequences* for the other contexts; and (3) the *choice among alternatives* in one context can be a means for achieving the underlying values important in the other contexts.

A key factor in integrating climate change adaptation and mitigation into sustainable risk management is to understand the processes of decision making at different scales. The distribution of costs and benefits of mitigation and adaptation differ -- e.g., mitigation benefits more global, adaptation benefits often more localized , the research

and policy discourses are often unrelated, and the constituencies and decision-makers are often different (mitigation may involve powerful industrial stakeholders from the energy sector concentrated at higher levels of decision making, while adaptation may involve more dispersed stakeholders at the local level across sectors) (Wilbanks, et al., 2007). To significantly reduce total global emissions, mitigation decisions must be taken either by major emitters, or by groups of countries. At the national and international level, the direct responsibility to curb the main drivers of global climate change are dispersed across countries (Banerjee, 2012). In contrast, adaptation often falls to practitioners where local responsibility is clearer, although it often depends on support from national and global scale (Tanner and Allouche, 2011).

In many cases, the challenge of fostering synergies while avoiding negative feedbacks is most likely to come into focus in place-based discussions of climate change responses and development objectives such as localities and small regions (Wilbanks, 2003; Bulkeley and Schroeder, 2012). Globally, a particular hurdle is applying available mitigation resources only for reducing emissions beyond that which would have occurred without those resources ("*additionality*") while recognizing that access to resources for adaptation efforts should take into account the critical role of *co-benefits* in supporting development in other ways while at the same time reducing vulnerabilities to climate change impacts (NRC, 2010a; also see section 20.4.1).

Choices in integrating adaptation and mitigation will vary according to the circumstances of each locality (de Boer et al., 2010). In the more highly vulnerable countries, adaptation may be seen as the highest priority because there are immediate benefits to be obtained by reducing vulnerabilities to current climate variability and extremes as well as future climate changes. In the case of developed countries, adaptation initiatives have often been seen as a lower priority because it is perceived that there is abundant adaptive capacity (Naess et al., 2005). Yet major loss and damage in some industrialized countries related to climatic variability and extremes between 2010 and 2012 challenge this perception (e.g., Hurricane Sandy, tornadoes, and drought in the US in 2011 and 2012). Mitigation may be seen as more acute political question—involving well-organized stakeholders concerned about costs—in countries that contribute a large proportion of GHG emissions.

As indicated above, one emerging strategy to integrate between climate and development policies is the design of "triple-win" interventions that seek to achieve an appropriate mix of mitigation and adaptation within the context of sustainable development (Pyke et al., 2007; Swart and Raes, 2007). Swart and Raes (2007) suggest a number of factors that should be taken into consideration when evaluating combined adaptation and mitigation policy designs, including: (1) *avoiding trade-offs* - when designing policies for mitigation or adaptation, (2) *identifying synergies*, (3) *enhancing response capacity*, (4) *developing institutional links* between adaptation and mitigation - e.g. in national institutions and in international negotiations, and (5) *mainstreaming* adaptation and mitigation considerations into broader sustainable development policies. The potential for climate-resilient pathways may already be limited, however, in part because of path dependency stemming from choices on mitigation, adaptation, and political interpretations and subsequent choices around "sustainable" development (Barker, 2008; Swart et al., 2003); and in many cases interventions have not delivered win-win results because tradeoffs were not avoided (Warner, van der Geest, et al., 2012).

In synthesizing evidence from a series of empirical articles focusing on the intersection between mitigation and adaptation (M&A), Wilbanks and Sathaye (2007) argue that mitigation and adaptation pathways might be alternatives in reducing costs, complementary and reinforcing to each other (e.g., improvements in building energy efficiency), or competitive and mutually contradictory (e.g., coastal protection vs. reductions in sea level rise). In Bangladesh, for example, waste-to-compost projects contribute to mitigation through reducing methane emissions; to adaptation through soil improvement in drought-prone areas; and to sustainable development through the preservation of ecosystem services (Ayers and Huq, 2009; also see Vergara et al., 2012, regarding possible development benefits of mitigation and adaptation in Latin America and the Caribbean). The scale of these examples is often local, however, and longer-term success of these pathways will depend on the broader context of mitigation and facilitation of adaptation options (Metz, 2002).

When integrating across the goal of finding climate resilient pathways (and win-win solutions), decision-makers often need to address issues of scale, along with trade-offs in values such as economic profitability versus stability of food and livelihood security (e.g. in agricultural policy), relationships between development ends and means,

uncertainty and path dependencies, and institutional complexity (Klein, Schipper, and Desai, 2005; Tol, 2004; Wilson and McDaniels, 2007). They also need to consider the possibility of ancillary co-benefits, complementarities and potential contradictions, opportunity costs, and unknown negative and positive feedbacks (for example interactions among options and paybacks (NRC, 2010a; Kok et al., 2008; Wilbanks and Sathaye, 2007; Swart and Raes, 2007; Rosenzweig and Tubiello, 2007; IPCC, 2007: Chapter 18). Current research is examining tradeoffs and complementarities between mitigation and adaptation in different sectors. In the energy sector, for instance, Kopytko and Perkins (2011) have examined to what extent the siting of nuclear power plants might constrain future adaptation to sea-level rise. Others ask how the production of biofuels might affect local adaptation (La Rovere, Avzaradel, and Monteiro, 2009); agriculture and water (Rounsevell et al., 2010; Turner et al., 2010; Rosenzweig and Tubiello, 2007; Falloon and Betts, 2010; Shah, 2009); conservation (Rounsevell et al., 2010; Turner et al., 2010); use of mitigation programs to finance adaptation (Hof et al., 2009); and the urban environment (Biesbroek, Swart, and van der Knaap, 2009; Hamin and Gurran, 2009; Roy, 2009; Romero-Lankao et al., 2011).

20.4. Contributions to Resilience through Sustainable Development Strategies and Choices

Although climate change responses can contribute significantly to climate-resilient development pathways, some of the key elements of resilience lie in sustainable development implementation, which can make resilience either more or less achievable. Examples of ways that development strategies and choices can contribute to climate resilience include being capable of resolving tradeoffs among economic and environmental goals (e.g., Bamuri and Opeschoor, 2007), assuring effective institutions in developing, implementing, and sustaining resilient strategies, and enhancing the range of choices through innovation (e.g., Hallegatte, 2009; Chuku, 2009; Folke et al., 2002).

20.4.1. Resolving Tradeoffs between Economic and Environmental Goals

Sustainable development pathways will be more climate-resilient if they develop and utilize socioeconomic and institutional structures that are effective in resolving tradeoffs among social, economic, and environmental goals – a central tenet of sustainable development (section 20.2.1.1).

There is a longstanding assumption that economic growth is in conflict with environmental management (Victor and Rosenbluth, 2007; Hueting, 2010). Much of this thinking can be traced back to Malthus and his assertions that population growth (and associated consumption) would expand at an increasing rate until the limits of the earth's capacity were reached (Malthus, 1798). The very idea of sustainable development itself springs from a need to respond to such Malthusian ideas. The views expounded in the Brundtland Report, for example, are that development should not be unconstrained but should rather be modified into a "sustainable" form (WCED, 1987). Views about relationships between economic growth and environmental protection range widely from arguments that sustainable development is inconsistent with continued economic growth (e.g., Robinson, 2004) to arguments that economic growth and associated technological innovation can enhance options for environmental management (Lovins, 2011). Obviously, relationships between affluence and environmental protection are complex, as poverty can lead to land degradation and affluence can afford support for nature preservation, while economic growth is built on levels of resource extraction and use that require significant changes in environments. Sustainable development cannot escape continuing tensions between economic growth and environmental management goals, where strongly held views across society often differ so fundamentally that conflict results unless social processes and institutional mechanisms are effective in resolving s host of tradeoffs (Boyd et al., 2008), with both values and processes varying according to development context.

Examples of frameworks of thought often related to addressing tradeoffs are multi-metric valuation and co-benefits (see also Ness et al., 2007, regarding tools for sustainability assessment, and Pew Center, 2010):

- *Multi-metric valuation*. In evaluating development pathways, there are often needs to combine a number of dimensions associated with different valuation metrics and information requirements, such as monetary measures of returns and non-monetary metrics of risk. Fields ranging from aquatic ecology to risk assessment and financial management have developed tools for such complex valuations, including graphical mapping (e.g., Rose, 2010) and the construction of multi-metric indexes (e.g., an index of "biotic

integrity": Johnston et al., 2011). More commonly in collective decision-making, however, analytical-deliberative group processes are used to evaluate, weight, and combine different dimensions and metrics qualitatively (NRC, 1996).

- *Co-benefits*. An issue in both climate and development policy, related in some cases to access to financial support (e.g., Miller, 2008), is the fact that a specific resilience-enhancing action may have benefits for both development and for addressing concerns about climate change . International funding for mitigation projects has historically adopted the concept of "additionality," which takes the position that financial support should be limited to those climate change response benefits that are *in addition to* what would be happening in development processes otherwise (e.g., Muller, 2009). This general concept (e.g., "incremental" costs and benefits) has been applied in financial support for adaptation as well. A co-benefits approach, on the other hand, takes the position that actions which benefit *both* development and climate change responses simultaneously should be encouraged and that a combination of both kinds of benefits should increase the attractiveness of a proposed action (section 20.3.3; also see http://www.kyomecha.org/cobene/e/cobene.html and IPCC Working Group III: Chapter 6). For example, mechanisms such as REDD are designed to achieve both carbon emissions reduction and to benefit livelihoods of those living in forested areas. However, empirical research shows that the evidence of the correlation between carbon storage and livelihoods benefits is mixed (Chhartre and Agrawal, 2009). Tools for analyzing such issues are associated with research on "externalities" (e.g., Baumol and Oates, 1989), but participative planning and decision-making usually incorporate a co-benefits perspective as a matter of course.

In practice, tradeoff issues may or not be resolved in coherent ways (Metz, 2002). In many cases, resolutions emerge through untidy social processes of evolution and attrition, reflecting dynamics of values, power, control, and surprises, rather than through formal analysis. In some cases, tradeoffs are addressed with the assistance of scenario development, the creation of descriptive narratives, and other projections of future contingencies (IPCC SREX: Chapter 8), along with participative vulnerability assessments (NRC, 2010a).

20.4.2. Assuring Effective Institutions in Developing, Implementing, and Sustaining Resilient Strategies

Climate resilience will benefit from institutions that are effective and flexible in the face of a wider range of challenges for problem-solving and issue resolution as well. "Institutions" refer not only to formal structures and processes but also to the rules of the game as well as the norms and cultures that underpin environmental values and belief systems. Ostrom (1986) defines institutions as the rules, norms and practices defining social behavior in a particular context, the action arena. Institutions define roles and provide social context for action and structure social interactions (Hodgson, 2003). Definitions of sustainability are largely shaped by institutional values, cultures and norms. Institutions also critically define our ability to govern and manage the resources and systems that shape adaptation, mitigation and sustainable development. Adopting an adaptation and mitigation pathway requires strong institutions that are able to foster an enabling environment through which adaptive and mitigative capacities can be built (Gupta et al., 2010; IPCC, 2007: Chapter 20). Implicit in institutional resilience is the capacity of the exposed unit and the players within an action arena to devise rules that allows them to recover from environmental shocks, and equally ones that provides incentives and benefits that equitably distributes resources across social groups (Denton, forthcoming; McSweeny and Coomes, 2011). Hence, the trajectory to a resilient pathway needs an institutional leap, one that knowingly set rules, seeks to innovate, monitor and evaluate strategies for managing climate impacts.

Transformative action and change in integrating sustainable development within a framework of climate resilient pathways is in fact rooted in strong and viable institutions and within an institutional context that adaptively manages the allocation of resources and processes of change. Institutions at different levels have been the object of societal pressures and challenges relating to environmental change. Local institutions are particularly adroit in coping with multiple changes. These changes often force local actors and organizations to rethink their institutional arrangements and make adjustments that will allow them to cope with multiple vulnerabilities (McSweeny and Coomes, 2011). Organizational mechanisms are central to building linkages between local level adaptation action and national level planning; however, in six cases studies in West Africa and Latin America, Agrawal et al. (2011)

found that while these connections are missing in almost all the countries studied, external policy support can catalyze adaptation action through three types of intervention mechanisms– information, incentives, and institutions.

Institutions for integrated climate-resilient pathways are therefore not limited to governmental institutions; in fact, in many cases a majority of the key decisions are made and implemented by non-governmental actors, from the private sector to communities and families. For instance, in projects supported by the IDRC/DfID Climate Change Adaptation in Africa Programme (CCAA), in both Tanzania and Morocco, local governments are providing improved seeds that are drought resistant to vulnerable groups and financially supporting initiatives at community level (Denton, forthcoming). Embarking on a climate resilient pathway may necessitate including local institutions as part of the governance regime. Similarly, as local communities become more exposed to climate extremes and variability, they are already adapting to the negative impacts of climate variability and change. However, a sustainable route depends largely on the organisational capacity of vulnerable groups and their ability to translate challenges into opportunities. For example, in Morocco, where local communities have strong institutions, such as in the Tabant mountain community, they were found to be adapting collectively; but where institutions were less effective and weak, as in the arid plain of Lamzoudia, adaptation action was characterised by individual initiatives (Denton, forthcoming)

In particular, local institutions crucially influence the ability of communities to adapt and benefit from adaptation and mitigation programs in rural and urban settings (Agrawal, 2008; Chhartre and Agrawal, 2009; Corbera and Brown, 2008). For instance, institutions tend to play an influential role in shaping farmers' decisions and helping them make strategic choices with several implications for livelihoods and sustainable development (Agrawal, 2008). In rural areas, current socioeconomic dynamics, rapid population growth, commercialized agriculture, new agricultural trends and technological advancements in agriculture have meant that local institutions have seen a change in their role in governing environmental management in adaptive governance. Local institutions are themselves in a state of flux as they are subjected to uncertainties in climatic condition (Senaratne and Wickramasinghe, 2010*)*. However, in developing countries, particularly in Africa, where traditional knowledge could moderate this uncertainty, it is often not recognized as a reference point for managing climate risks and emerging threats. In Kenya, the importance of indigenous knowledge, given increased uncertainty and climate related risks, has compelled national agencies such as the Kenyan Meteorological Agencies and vulnerable groups such as the indigenous communities commonly known as rainmakers to form strategic reciprocal links. By working closely together to calibrate their forecasts and test the efficacy of the results against climate change impacts on agricultural productivity, the two groups have been able to demonstrate the benefits of western science and traditional knowledge systems to ensure maximum effectiveness (Ziervogel and Opere, 2010). In addition, participatory processes which call for a deliberative form of decision making among stakeholders are well suited to the governance culture necessary for effective adaptation and mitigation. Scholars have found that deliberative processes of democracy provide greater efficacy in decision-making and lead to more sustainable outcomes. They argue that some deliberative democracy methods can bring diverse stakeholders together- lay, expert and indigenous knowledge - thus putting in place a more communicative model of science (Benn, Dunphy, and Martin, 2009), although stakeholder participation does not always lead to consensus (Rowe and Frewer, 2004).

In addition, institutions are also needed to handle the large flows of funds and other resources that are associated with managing and improving the delivery systems that will allow people and organizations to take advantage of opportunities that will trigger a set of actions to combat the negative impacts of climate change. The complexity of different resource flows and distributional effects related to adaptation and mitigation is at the heart of the sustainable development debate, with numerous implications for equity and justice (O'Brien and Leichenko, 2003; Roberts and Parks, 2006). The nature and dynamics of climate change call for institutions that are able to facilitate the enhancement of adaptive capacity and 'allow society to modify its institutions at a rate commensurate with the rapid rate of environmental change' (Gupta et al., 2008). Institutional 'renewal' is essential to achieve a degree of social cohesion and transformation. A case study in Morocco, under the Climate Change Adaptation in Africa (CCAA), showed that the `Cellule de Littoral`, created to serve as a consultative committee on coastal development in Morocco, has gained some recognition at both local and national levels as it is integrated formally into the institutional framework for the implementation of Integrated Coastal Zone Management Plans of Action (Denton, forthcoming).

An institutional response to climate change is even more fundamental in common pool property resources especially in river basin management. River basins are considered as public goods. However, in a changing climate many river basins are subjected to increased precipitation or water scarcity that is affecting both marine life as well as livelihoods structures of the most vulnerable. A climate resilient pathway is one that will not only manage biophysical changes, but address inherent institutional asymmetries that can further reinforce current inequalities in the way common pool resources are managed.

The quality and performance of institutions are largely predetermined by the rules they follow and the suitability of these rules based on the biophysical and social setting. In addition, the evaluative mechanism in place as checks and balances and the players within the institutions and their receptiveness to follow the rules are all necessary preconditions for climate resilient pathway. For example, the monitoring capacity of the institution/s, as well as mediation capacity and the degree to which these are embedded at different scales across the governance regime will largely determine its adaptive capacity and sustainability. Thus, the vulnerability of large river basins will largely depend on the changing biophysical conditions, but also on institutional architecture that is put in place to manage risks and build resilience. For instance, Schlager et al argue that compacts that have fixed allocation rules tend to exhibit greater vulnerability to climate change mainly because the system is far too rigid and does not allow for much flexibility in dealing with the changing hydrologic regime. Building resilience to climate change impacts are largely predetermined by the flexibility of the institutions to change the rules according to the changing biophysical and social setting. For instance, states such as Colorado in the United States, have dealt with water scarcity more efficiently mainly because users of the basin have access to venues that allow them to design and review current rules (Schlager, E. and Heikkila, 2011).

It is, however, important to note that institutional arrangements are not the only determining factor in bringing about transformational change. For instance, Agrawal et al. argues that there is a strong likelihood that technological improvements and institutional arrangements can positively affect the causal relationship between ecological sustainability and social equity (also see Agrawal and Benson, 2011).
Common problems with institutional roles include a frequent incompatibility of current governance structures with many of those that may be necessary for promoting social and ecological resilience' and the fact that 'adaptive ecosystem management overturns some major tenets of traditional management styles which have in many cases operated through exclusion of users and the top-down application of scientific knowledge in rigid programmes' (Tompkins and Adger, 2004: 10).

20.4.3. Enhancing the Range of Choices through Innovation

Finally, climate resilience will in most cases depend on innovation, developing new ideas and options or adapting robust familiar ideas and options to meet emerging new needs and to respond to surprises (also see IPCC Working Group III: Chapter 6). As indicated in the previous section, integrated strategies for climate resilience can benefit from considering possibilities to develop new options through social, institutional, and technological innovation. For example, if a climate-resilient pathway for a particular region calls for coping with greater water scarcity, innovations might consider changes in water rights practices, improving the understanding of groundwater dynamics and recharge, improving technologies and policies for water-use efficiency improvements, and in coastal areas the development of more affordable technologies for desalination (NRC, 2010a; Lebel, 2005). One key issue for risk management, therefore, is assessing needs for and possible benefits from targeting innovation efforts on critical vulnerabilities.

Innovations can include both technological and social changes, which in many cases are closely related (Rohracher, 2008; Raven et al., 2010), as technology and society evolve together (Kemp, 1994). An important characteristic of such socio-technical transitions are the interactions and conflicts between new, emerging systems and established regimes, with strong actors defending business as usual (IPCC SREX, 2012; Kemp, 1994; Perez, 2002).

Effective use of innovations depends on more than idea and/or technology development alone. Unless the options, the skills required to use them, and the institutional approaches appropriate to deploy them are effectively transferred from providers to users, effects of innovations – however promising – are minimized (IPCC SREX,

2012). Challenges in putting science and technology to use for sustainable development have received considerable attention (e.g., Nelson and Winter, 1982; Patel and Pavit, 1995; NRC, 1999; International Council for Science, 2002; and Kristjanson et al., 2009). These studies emphasize the wide range of contexts that shape both barriers and potentials and the importance of "co-production" of knowledge, integrating general knowledge with local knowledge, experience, and expertise. If obstacles related to intellectual property rights can be overcome, however, the growing power of the information technology revolution could accelerate the transfer of technologies and other innovations (linked with local knowledge) in ways that would be very promising for strengthening local resilience (Wilbanks and Wilbanks, 2010).

20.5. Determinants of Resilience in the Face of Serious Threats

Climate change is not the only threat facing societies in the 21st century; many households, communities and regions are addressing poverty, inequality, and a confluence of economic, demographic, social and cultural changes. As discussed in Chapter 13, future impacts of climate change and extreme events can slow down the pace of poverty reduction in urban areas, further erode food security, and jeopardize sustainable development. IPCC's Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC SREX, 2012) concluded that – due to climate change – climate extremes and extreme events will pose increasing challenges for natural and human systems. Successful responses to climate change will involve both incremental and transformational adaptations, with the latter dependent upon the timing and ambition levels of global greenhouse gas mitigation efforts, as well as on the choice of development pathways (Rogelj et al., 2013; Peters et al., 2013; Box 20-3).

20.5.1. Relationships between the Magnitude and Rate of Climate Change and Requirements for Transformational Adaptation

Climate-resilient pathways recognize a wide range of stressors and threats, including those linked to economic, political, social and technological changes. The complexity of these non-linear, interacting changes introduces both uncertainty and surprises. Resilience is a concept that that takes into account how a system, community, or individual can deal with disturbance, uncertainty and surprise over time (Folke et al., 2010; Walker and Salt, 2006). It can be defined as the ability of a social, ecological, or socio-ecological system and its components to anticipate, prevent, reduce, accommodate, adapt or recover from the effects of a hazardous event in a timely and effective manner (see Glossary). Anticipation focuses on real or imagined changes that are different from the present situation or status quo. Scenario development, storylines, and other anticipatory systems can be used to identify potential future outcomes based on an analysis of systemic, interacting changes (Miller, 2007; van Vuuren et al., 2012; Kriegler et al., 2012; IPCC SREX, 2012: Ch8). Prevention considers the social, economic, cultural, and political costs of anticipated futures and addresses them within an ethical framework (Gardiner 2004; Warner, van der Geest, et al., 2012). It is a conservative action that is dependent upon risk analysis frameworks (See Chapter 1, Chapter 2), as well as on understandings of the barriers and limits to adaptation (see Chapter 16).

In the absence of prevention, resilience involves reducing, accommodating, adapting to or recovering from the outcomes of climate change. For example, current strategies to reduce vulnerability to increased flooding involve new ways of accommodating water in landscapes (Delta Commission, 2008), and new types of adaptations to changes in the frequency and magnitude of floods (Environment Agency, 2009; Milly et al., 2008). The distinction between incremental adaptation and transformational adaptation is significant: Incremental adaptation can be considered extensions of actions and behaviors that already reduce losses or enhance benefits associated with climate change, often where the goal is to maintain the essence and integrity of an incumbent system or process at a given scale (Kates et al., 2012; Park et al., 2012). Transformational adaptation, in contrast, includes actions that change the fundamental attributes of a system in response to actual or expected impacts of climate change. These may involve adaptations at a greater scale or intensity than previously experienced; adaptations that are new to a region or system; or adaptations that transform places or lead to a shift in the location of activities (Kates et al., 2012). Such transformations are expected to occur when the rate and magnitude of climate change threatens to overwhelm the resilience of existing systems, or when vulnerability is high (Kates et al., 2012). There is growing

evidence that climate change is going to be significant enough for many locations and systems that climate-resilient pathways will have to consider transformational change in advance of disruptive impacts in order to reduce risk and vulnerability (see Chapters 14-17). Transformational adaptation often occurs in continuous interaction with incremental adaptations (Park et al., 2012, see IPCC SREX, 2012, Figure 8-1). However, the rate and magnitude of climate change can influence the resilience of the system, in some cases undermining the capacity to adapt to change, and introduce limits to adaptation (Adger et al., 2009; Marshall et al., 2012).

Estimates of loss and damages associated with climate variability and change over time suggest that the rate and magnitude of climate change has significance for sustainable development (IPCC SREX, 2012; Beddoe et al., 2009; Warner, van der Geest, et al., 2012). The severity of climate change is influenced by the rate and timing of greenhouse gas emissions (Kriegler et al., 2012). Model results based on integrated scenarios that take into account geophysical, technological, social and political uncertainties indicate that achieving the often-discussed 2°C average global temperature increase calls for mitigation of emissions through increased energy efficiency and lower energy demand well before 2020 (Rogelj et al., 2013; Peters et al., 2013; section 20.6.1). In the absence of ambitious mitigation efforts, the future impacts of climate change can be expected to be non-linear, with the potential for crossing thresholds and tipping points (Lenton, 2011a). Although thresholds or tipping points in complex systems are difficult to predict, studies from a variety of disciplines indicate some generic properties associated with transitions between different states. Indicators of critical transitions include an increase in recovery times from disturbances, and changes in spatial patterns (Scheffer et al., 2009).

Because of the large negative impacts of crossing climate tipping points, such scenarios are important to include in risk assessments and response strategies. An analysis of historical collapses of ancient states or civilizations indicates that transformations at a large social or spatial scale are associated with multi-causality with cascading feedbacks, and that collapses can be avoided by through collective strategies that contribute to socio-ecological resilience (Butzer and Endfield, 2012; Butzer, 2012; Dugmore et al., 2012). Such resilience calls not only for adaptability, but also for transformability (Folke et al., 2010; Westley et al., 2011). Consequently, in addition to transformational adaptation and transformations to low-carbon societies, there is increased attention to the importance of transformations for global sustainability, which in many cases include social transformations (Folke et al., 2009; Pelling, 2010; Westley et al., 2011).

20.5.2. Elements of and Potentials for Transformational Change

Given the risks of climate change and associated impacts on natural and managed resources and systems, human settlements, industry, infrastructure, health, well-being, and human security, and given the limits to adaptation discussed in Chapter 16, there are increasing calls for deliberate transformations towards global sustainability (Raskin et al., 2002; WBGU, 2011; Westley et al., 2011; O'Brien, 2012). Global sustainability includes the goals of sustainable development, but considers them within the context of planetary and social boundaries (Rockström et al., 2009; Leach et al., 2012). Transformation is defined as a change in the fundamental attributes of a system, often based on altered paradigms, goals, or values. Transformations can occur in technological or biological systems, financial structures, and regulatory, legislative, or administrative regimes (see glossary). Transformation in wider political, economic and social systems can either open up or close policy spaces for more resilient and sustainable forms of climate responses, particularly where contemporary development pathways are identified and addressed as part of the root causes of vulnerability (Pelling, 2010; IPCC SREX, 2012: Chapter 8).

There is an extensive literature on transitions and transformations, covering a variety of sectors and factors that influence changes in systems and behaviors (Calvin et al., 2009; Berkhout et al., 2010; Shove and Walker, 2010; Pelling 2010; Geels, 2002; IPCC Working Group III: Chapter 6). Transformation can be triggered by events, but often they are long-term processes (Loorbach, 2007). Factors that may improve prospects for both initiating and sustaining transformations can include dramatic focal events that catalyse attention to vulnerabilities; the presence of other sources of stress that also encourage considerations of major changes; and supportive social contexts such as the availability of understandable and socially acceptable options, access to resources for action, and the presence of incentives. Transformation is also linked to adaptive leadership, empowerment and collaboration within and across institutions, organizations and groups (IPCC SREX, 2012: Chapter 8; Heifetz et al., 2010; Kates et al., 2012; Moser

2013). Other key elements associated with transformations include adaptable institutions (cultural, economic and governance), all types of capital, diversity in landscapes, seascapes and institutions, learning platforms, collective action and networks, as well as reflexivity and the capacity to take perspectives (Loorbach 2007; Folke et al., 2010; Westley et al., 2011; Schlitz et al., 2010). Many of the elements of climate resilient pathways discussed in Box 20-5 can, in fact, support transformation.

While transformations may be reactive, forced or induced by random, stochastic factors, they may also be deliberately created (Folke et al., 2010; O'Brien, 2012; Kates et al., 2012). Deliberate transformations can take place across interacting spheres, referred to by O'Brien and Sygna (forthcoming) as the practical, political and personal spheres of transformation (see Figure 20-2). The practical sphere includes social and technological innovations, behavioral changes, and institutional and managerial reforms that directly influence outcomes. Although this is where most attention is currently focused, transformations in this sphere are challenging because they seldom question or address larger systems and structures. Consequently, the lines between business-as-usual and transformation in this sphere are easily blurred. The political sphere represents the economic, political, legal, social and cultural systems that define the boundaries within which practical transformations take place. It is within this sphere where problems and solutions are identified and defined, and where value conflicts are often experienced and resolved. The political sphere is often a reflection of dominant cultural beliefs and worldviews that are seldom recognized or questioned. These involve transformations in the personal sphere, which includes individual and collective beliefs, values and worldviews that shape the ways that systems and structures are viewed, as well as the practical solutions that are considered possible. Transformations in this sphere often represent paradigm shifts that can influence both political and practical interventions. Whether in relation to transformational adaptation, transformation to low-carbon societies, or transformations to global sustainability, attention to all three spheres is considered necessary in response to the observed and anticipated impacts of climate change (Beddoe et al., 2009). As discussed in the next section, climate resilient pathways may involve conflicting goals and visions for the future, and not every transformation is considered equally ethical, equitable or sustainable. The normative dimension of climate change responses and climate resilient pathways is thus an important part of both discussions and actions related to sustainable development.

[INSERT FIGURE 20-2 HERE
Figure 20-2: The three spheres of transformation.]

20.6. Toward Climate-Resilient Pathways

20.6.1. Alternative Climate-Resilient Pathways

Climate-resilient pathways consist of future trajectories of development that combine adaptation and mitigation in the context of sustainable development implementation. At any scale (local or regional) there are multiple paths leading to the same total amount of climate resilience: alternative stable states (Hollings, 1973). At any time period along a pathway, more or less resilience maybe observed at specified points within the system (or locality), while the total amount of resilience within the entire system remains unchanged (Folke, 2006). Each potential alternative pathway can be strengthened and evaluated based on certain risk management characteristics/elements, the capacity to: a) foresee risk/vulnerability, b) decrease climate change impacts, c) respond rapidly to unpredictable, uneven and extreme events, d) include considerable amounts of proactive adaptation, and e) evolve in support of societal advancement and balanced environmental management.

Many of the choices involved in framing and supporting attempts to increase and sustain climate resilience are made largely at global and national levels, but many of the actions to sustain resilience are made at local levels. The global pathways that emerge are accumulations of these local and national choices. In these processes, path dependence is strong enough such that risk management decisions in the near term are more likely to lead to resilience if long term objectives are included as well as a wider spatial scale up to and including the global level.

A central issue in considering alternative pathways is the extent to which they may fail to meet a criterion of climate resilience. Or to put the question more simply, "are there any boundaries on the envelope of climate resilience"? The

answer is highly scale dependent. We have a carbon legacy in the atmosphere, and total prevention/avoidance of impacts is now unachievable (Dickinson, 2007). At any level of stabilization of GHG concentrations, with even the strongest emissions reduction targets, some localities or systems or populations will be vulnerable to disruptions because there is in effect no limit below which universal prevention of residual loss and damages can be assured. Transformational change will therefore need to be a key component in nearly all alterative climate resilient pathways.

In the event that global surface mean temperatures rise through +2ºC to +4ºC and higher (Schneider, 2009; New et al., 2012; Anderson and Bows, 2008), sustainability will become significantly more difficult to achieve (food security is a notable example: Chapter 7). For example, a business-as-usual future society where unsustainable development paths are the norm, where technology transfer between countries is lacking, population growth increases rapidly, GHGs emission go unabated, and institutions and governance structures are ineffective at creating effective climate change policies, would almost certainly result in losses so widespread that development pathway would not be resilient (Riahi et al., 2011; Arnell et al., 2013). A pathway that included these elements would fall outside the 'boundaries of the envelope of climate resilience'.

Within these boundaries, climate-resilient pathways can be made up of a collective of alternative choices at the regional level, where they are dependent upon specific demographics, potential for economic development and growth, ecological and ecosystem services, access to natural resources, institutional and governance structures, and technological development and transfer. The concept of Shared Socioeconomic Pathways (SSPs) at the global level offers one framework for considering alternative mixes of actions in support of climate resilience (Box 20-3). SSPs consider alternative socioeconomic pathways according to dimensions related to both the resource intensity of economic growth and the effectiveness of institutions in resolving tradeoffs (Kriegler, et al., 2012). Five notional pathways have been developed to illustrate a range or possible futures, as a basis for discussion, with each SSP following a distinct storyline (Figure 20-3). These dimensions can then be related to socioeconomic challenges confronting climate change mitigation and adaptation (as one aspect of sustainable development). In Figure 20-3, Pathway 1 has relatively limited challenges to both adaptation and mitigation, while Pathway 3 has substantial challenges to both adaptation and mitigation. Any pathway characterised by low challenges to both is likely to be climate- resilient at the global scale and in many local or national situations. A pathway characterised by high challenges to both adaptation and mitigation is less likely to be climate-resilient at the global scale and in many localities and countries.

[INSERT FIGURE 20-3 HERE
Figure 20-3: A notional depiction of alternative climate-resilient sustainable development pathways (lower left). Regarding SSPs, see Box 20-3; SSPs are representations of alternative socioeconomic pathways within which climate change responses might evolve.]

Considering alternative climate-resilient pathways cannot be separated from levels of climate change. In principle, most climate change scientists, decision-makers, and stakeholders agree that: (a) there is a level of climate change that is low enough that climate resilience for most systems could be achieved without enormous efforts and widespread transformational adaptation; (b) there is a level of climate change that is high enough that climate resilience cannot be expected to cope with severe impacts on most systems (e.g., Rockstrom et al., 2009); and (c) between those two levels the challenges to climate resilience grow as the level of climate change rises. Scientists do not, however, agree on what magnitude of climate change (e.g., average global warming) defines each of the two levels. Some experts support the view (Box 20-1 and section 20.3.1) that any level above 2 degrees C would mean impacts that are incompatible with sustainable development (Metz et al., 2002**).** IPCC's Fourth Assessment Report concluded that there is an approximate threshold, between 2.5 and 3 degrees C of warming, above which impact concerns are severe but below which concerns are less severe (IPCC, 2007). Other scientists are unconvinced that system sensitivities to climate parameters such as temperature increase are well-enough understood to support any specific warming threshold (e.g., NRC, 2010c), and some scientists and policymakers are unconvinced that adaptive response capacities are well-enough understood to support determinations of limits to adaptation and resilience (Chapter 16). Most experts in all three groups, however, agree that prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation (e.g., New et al., 2012).

20.6.2. Implications for Current Sustainable Development Strategies and Choices

Although payoffs from specific long-term pathways may be uncertain at this time, such uncertainties need not preclude actions now. Climate-resilient development pathways are not about actions taken in the future, but rather about the strategies and choices that are taken today. The range of potential climate outcomes, discussed in Box 20-3, will have dramatically different implications for human security, as well as for the health and status of species and ecosystems (IPCC WGII, AR5). Increasingly, the literature linking climate change to greenhouse gas concentrations shows that the emissions in the coming decades will be decisive for future climate outcomes (Anderson and Bows, 2008; Meinshausen et al., 2009; Solomon et al., 2009).

In fact, waiting to take action may reduce the range of choices for climate resilient pathways in the future (NRC, 2011b). The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), 2012, makes the case that a "solution space" exists now for considering possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. It suggests that a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways. The solution space emphasizes the linkages between different strategies, recognizing that no single approach alone is likely to be sufficient.

Meanwhile, in some parts of the world, current failures to address effects of emerging climate stressors are already leading toward adaptation strategies that erode bases for sustainable development Damage and loss patterns are not limited to future vulnerabilities; in many areas they are impeding food production and other essential development services in ways that are clearly non-sustainable (Warner and Afifi 2012a; Warner, van der Geest, et al., 2012).

In discussing approaches to sustainability in the context of climate extremes, the SREX report draws attention not only to the role of incremental change, but also to transformation, which is defined as "the altering of fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems) (IPCC SREX, p. 564). Climate-resilient development pathways that deliberately address mitigation and adaptation through both incremental and transformative strategies are likely to present more options for sustainable development than those pathways that reactively respond to the challenges of climate change.

20.7. Priority Research/Knowledge Gaps

Simply stated, what is known about integrating climate change mitigation, climate change adaptation, and sustainable development is dwarfed by what is not known. If national and global decision-makers wish to realize potentials from a fusion of these three imperatives, then research should be a very high priority indeed. The most salient research need is to improve the understanding of how climate change mitigation and adaptation can be combined with resilient sustainable development pathways in a wide variety of regional and sectoral contexts (Wilbanks, 2010). One starting point is simply improving the capacity to characterize benefits, costs, potentials, and limitations of major mitigation and adaptation options, along with their external implications for equitable development, so that integrated climate change response strategies can be evaluated more carefully (Wilbanks et al., 2007; NRC, 2011). What are the major tradeoffs? What are the potential synergies? How do implications of integrated mitigation/adaptation strategies vary with location, climate change risks and vulnerabilities, scale, and development objectives and capacities? (e.g., Hugé et al., 2011). In these regards, the best of global science needs to be combined with national and local expertise to advance knowledge related to climate-resilient pathways.

Related to this general priority are at least three specific research needs:

1) Research on how to reconcile the importance of synergies between climate change adaptation and mitigation actions with widespread use of the concept of additionality, e.g., how to establish criteria for access to financial support for adaptation that incorporates the development importance of co-benefits. For

example, such research could inform discourses about differences between adaptation and development in ways that enable the flow of financial resources to support adaptations: e.g., how to acknowledge co-benefits in allocating investment resources without inviting every party seeking development investment to use climate change as an opportunity (NRC, 2010a).

2) Advances in conceptual and methodological understandings of, and tools to support research on, multiple drivers of development pathways and climate change impacts; possible feedback effects among mitigation, adaptation, and development; and possible thresholds/tipping points that could cause particular challenges for development (NRC, 2009, 2010a).
3) Advances in knowledge about how to respond sustainably to climate change extremes and extreme events, when and where they pose development challenges that would appear to require transformative changes in impacted human and/or environmental systems. What might the options be, and how can they be facilitated where they should be considered? (e.g., Pelling, 2010).

Further research needs include:

- Research attention to potentials for technological and institutional innovations to ease threats to sustainable development from climate change impacts and responses. In other words, how might climate change responses represent opportunities for innovative development paths? How might technological development be part of a strategy for development/climate change response integration? (Wilbanks, 2010)
- Research on strategies for institutional development, including improving understandings of how social institutions affect resource use (NRC, 2009), improving understandings of risk-related judgment and decision-making under uncertainty (NRC, 2009), and best practices in creating institutions that will effectively integrate climate change responses with sustainable development outcomes such as participation, equity, and accountability
- Research on strategies for the implementation of adaptive management for development. Examples of important research needs include improving the understanding of respective roles and interactions between autonomous response behavior and policy initiatives, improving the body of empirical evidence about how to implement changes that are judged to be desirable: e.g., adaptive management and governance capacity, and improving the understanding of differences between retrofitting older infrastructures (the challenge in many industrialized countries) and designing new infrastructures (the challenge in many rapidly developing countries) (IPCC SREX, 2012: Chapter 8).
- Research to improve the understanding of how to build social inclusiveness into development/climate change response integration. As suggested above, research is needed on issues of social values/climate justice/equity/participation and how they intersect with the deployment of mitigation, adaptation interventions and sustainable development policy in different regional/sociopolitical contests (IPCC SREX, 2012: Chapter 8).
- Research on factors that influence deliberate transformations that are ethical, equitable, and sustainable (O'Brien, 2012; Kates, Travis, and Wilbanks, 2012).
- The development of structures for learning from emerging integrated climate change response/development experience: e.g., approaches and structures for monitoring, recording, evaluating, and learning from experience, identifying "best practices" and their characteristics (NRC, 2010a; IPCC SREX, 2012: Chapter 8; Hilden, 2011).

Finally, it is very possible that progress with global climate change mitigation will not be sufficient to avoid relatively high levels of regional and sectoral impacts, and that such conditions would pose growing challenges to the capacity of adaptation to avoid serious disruptions to development processes. If this were to become a reality later in this century, one response could be a rush toward geoengineering solutions. In preparation for such a contingency, and perhaps as an additional way to show how important progress with mitigation will be in framing prospects for sustainable development in many contexts, there is a very serious need for research on geo-engineering costs, benefits, a wide range of possible impacts, and fair and equitable structures for global policymaking and decision-making (UK Royal Society, 2009; Kates, Travis, and Wilbanks, 2012).

But a fundamental aim of research to improve capacities for climate-resilient pathways for sustainable development is to avoid such an unfortunate outcome. It seeks to do so by strengthening the base of knowledge that underlies and

supports effective actions by viewing climate change mitigation, climate change adaptation, and sustainable development in an integrative and mutually supportive way.

Frequently Asked Questions

FAQ 20.1: Why are climate-resilient pathways needed for sustainable development?

Sustainable development requires managing many threats and risks, including climate change. Because climate change can no longer be avoided and, in fact, is a growing threat to development, sustainability will be more difficult to achieve for many locations, systems, and populations unless development pathways are pursued that are resilient to effects of climate change.

FAQ 20.2: What is a climate-resilient pathway?

A climate-resilient pathway for development is a continuing process of change management, combining flexibility, innovativeness, and participative problem-solving with effectiveness in mitigating and adapting to climate change. If effects of climate change are relatively severe, this process is likely to require considerations of transformational changes in threatened systems if development is to be sustained without major disruptions.

FAQ 20.3: Are there things that we can be doing now that will put us on the right track toward climate-resilient pathways?

Yes. We can carry out participative vulnerability assessments, look for ways to reduce vulnerabilities to effects of climate change that have other development benefits as well, monitor emerging climate changes and adaptive responses to improve our understanding of risks, and revise our vulnerability assessments and risk management strategies continually on the basis of growing evidence, knowledge, and experience. In many cases, these activities can be linked with other issues for sustainable development as well.

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Table 20-1: Effectiveness of water-saving irrigation dealing with climate change (Zou et al., 2012).

	2007	2008	2009
Water saved (Bm^3)	19.37-40.86	19.86-41.55	22.58-47.25
Energy saved (Mt)	2.92-6.39	3.08-6.72	3.58-7.73
CO_2 emission reduction (Mt)	6.66-14.58	7.02-15.31	8.15-17.59

Table 20-1: Examples of national plans for low carbon growth (Araya, 2010).

Country	Vision	Innovation
China	*Low carbon zones to provide a laboratory for large-scale low carbon private and public investment.* Europe-China collaboration to pioneer approaches compatible with Chinese institutions and development.	Low Carbon Zones build on 1980s Special Economic Zones (SEZs)
Maldives	Carbon neutrality by 2020 Climate change central development priority for government	Island with focus beyond adaptation
Mexico	Emissions peaking in 2012 and 50 percent reduction below 2000 levels by 2050 Establishment of low carbon development scenarios and priorities	2050 time horizon; peaking objectives; investment platform
South Korea	Plan to guide transition to low carbon economy 80 percent of economic stimulus package going into low carbon measures	Green recovery; public resources commitment
Japan	25% reduction in 2020 compared with 1990 level 80% reduction in 2050 compared with 1990 level Development of mid- and long-term roadmap	Mid- and long-term roadmap Subcommittee, Global Environmental Committee, Central Environmental Council

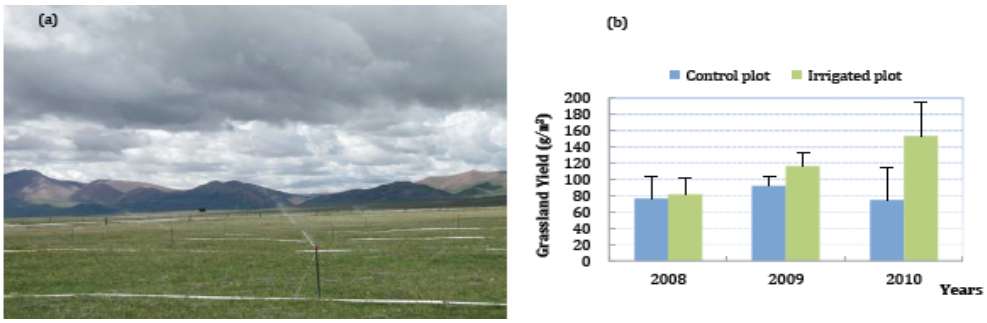

Figure 20-1: The demonstration of alpine grassland water-saving irrigation measures for adaptation to climate change in Northern Tibet.

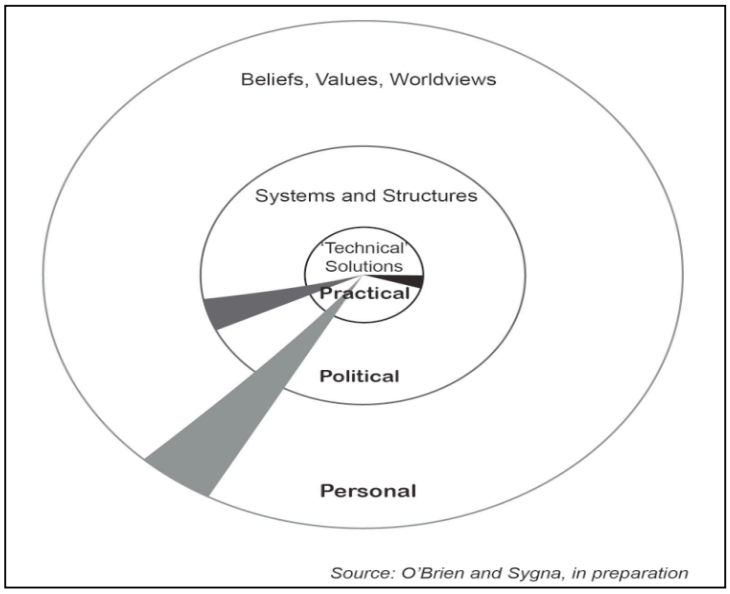

Figure 20-2: The three spheres of transformation.

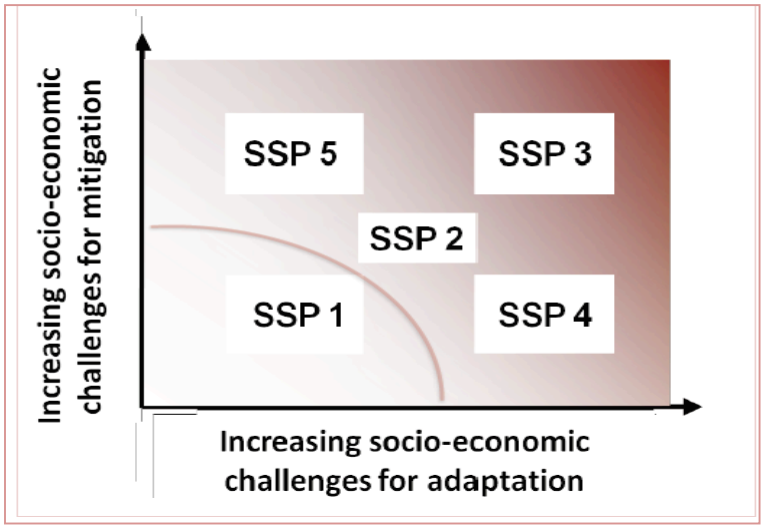

Figure 20-3: A notional depiction of alternative climate-resilient sustainable development pathways (lower left). Regarding SSPs, see Box 20-3; SSPs are representations of alternative socioeconomic pathways within which climate change responses might evolve.

Chapter 21. Regional Context

Coordinating Lead Authors
Bruce Hewitson (South Africa), Anthony Janetos (USA)

Lead Authors
Timothy Carter (Finland), Filippo Giorgi (Italy), Richard Jones (UK), Won-Tae Kwon (Republic of Korea), Linda Mearns (USA), Lisa Schipper (Sweden), Marten van Aalst (Netherlands)

Contributing Authors
Monalisa Chatterjee (USA), Grace Redmond ( ), Carol McSweeney (UK), Vanessa Schweizer (USA)

Review Editors
Thomas Downing (USA), Phil Duffy (USA)

Volunteer Chapter Scientist
Kristin Kuntz-Duriseti (USA)

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Cross-Chapter Box
CC-RC. Regional Climate Summary Figures

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Executive Summary

Regional responses to climate change are acutely affected by the information flow between disciplines, sectors and across scales. To bridge these requires special attention to communicating concepts, language, and the formulation of information tailored from one sector for another. Chapter 21 forms one such interface through framing a critical assessment of the regional context of thematic and sectoral issues in a decision-making context.

The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather and longer-term climate trends – are assuredly regional or local in their occurrence, character and implications. Explicit recognition of geographical diversity is therefore an imperative for any scientific assessment of anthropogenic climate change. [21.2.1] An understanding of the context in which risk plays out, and the alternative options that may be considered to manage it, are thus not an afterthought, but a defining feature of an appropriate climate analysis, requiring a close interplay between decision-makers and providers of climate change and climate risk information. In this context, understanding and responding to regional change requires recognition of key concepts, and of the relative strengths and weaknesses of information at the appropriate scales. [21.2.2]

There is diversity in knowledge about adaptation, vulnerability and impacts among and within regions around the world. Evidence available for different global regions on adaptation, vulnerability and impacts varies in terms of robustness, quantity, scope, and regional representativeness. [21.3.3] There is mounting evidence that human adaptation is very likely to be occurring as an autonomous response to ongoing climate change in some regions.

The scales at which political decisions about climate change need to be made are frequently at odds with the definitions of regions. Climate change transcends political boundaries and is highly variable from region to region in terms of impacts and vulnerability. Likewise adaptation policies, options, and mitigation strategies are strongly region dependent and tied to local and regional development issues. [21.3.2] Climate change policy at regional

scales is constrained by the dual challenge in achieving integration at multiple administrative scales from global through national to local (multi-level governance), and across different sectors (policy coherence). [21.3]

Cross-regional phenomena are very likely to be crucial for understanding the ramifications of climate change at regional scales, and its impacts and policies of response. [21.4] These include global trade and international financial transactions, which are linked to climate change as a direct or indirect cause of anthropogenic emissions, as a predisposing factor for regional vulnerability, through their sensitivity to climate trends and extreme climate events, and as an instrument for implementing mitigation and adaptation policies. Migration is also a cross-regional phenomenon, whether of people or of ecosystems, both requiring trans-boundary consideration of their causes, implications and possible interventions to alleviate human suffering and promote biodiversity.

Significant improvements have been made in the amount and quality of climate data that are available for establishing baseline reference states of climate-sensitive systems. [21.5.3] These include new and improved observational datasets, rescue and digitisation of historical datasets, and a range of improved global reconstructions of weather sequences. However, despite improvements, some questions remain unclear. For example, confidence in global precipitation estimates is low to medium due to incompleteness of data, and when all land areas are filled in using reconstruction methods, land precipitation shows little change since 1900 (in contrast to the AR4 assessment of a small increasing trend), along with a high degree of spatial and temporal variability in the trends.

Improved detection and attribution methods have shown that it is *extremely likely* that human activities have caused most of the global warming (more than 50%) since the 1950s and that this warming is not due to internal variability alone. The human influence on warming is *likely* over every inhabited continent (there are insufficient data to make an assessment over Antarctica). It is also *likely* that the human influence has altered sea level pressure patterns and related circulations. Attribution of changes in hydrological variables is less confident due to the lack of data though a human influence on zonal patterns of global and on high northern latitude precipitation changes has been detected (WGI Chapter 10).

Confidence in past and projected changes at regional scales is dependent on location and the variable being considered. Changes in global land surface air temperature exceed changes in global mean surface air temperature with continental interiors showing the largest changes. The increase in intensity of precipitation (and thus risk of flood) and summer drought occurrence over mid-continental land areas is a robust signature of global warming, both in observations for recent decades and in model projections. There is still little confidence in past trends and near term projections of tropical cyclone frequency and intensity. The mean regional pattern of sea surface salinity has been enhanced, with saline surface waters in the evaporation-dominated mid-latitudes becoming more saline, and relatively fresh surface waters in rainfall-dominated tropical and polar regions becoming fresher. It is virtually certain that the biogeochemical state of the ocean has changed (WGI Chapter 3). The uptake of CO2 by the ocean has resulted in a gradual acidification of seawater, with observations showing declines in pH in the mixed layer between -0.0015 and -0.0024 yr^{-1}. The retreat of Arctic ice in all seasons has continued, and the thickness, concentration and volume of arctic ice have also decreased. Conversely, the total extent of Antarctic ice has increased slightly with strong regional differences. Retreat of mountain glaciers is widespread, with varying rates across regions, and uncertainty about the global rate. Several hundred glaciers globally have completely disappeared in the last 30 years. Climate models indicate a nearly ice-free Arctic at the end of summer for warming greater than 2C. The models show no evidence of critical thresholds in the transition from perennial ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible. Projections of decrease in Northern Hemisphere spring snow covered area in the CMIP5 models are fairly coherent.

The uncertainty in near term climate projections is dominated by internal variability of the climate system, initial ocean conditions and inter-model response, rather than GHG forcing. The internal variability grows in importance at smaller spatial and temporal scales. The CMIP5 ensemble includes a new set of multidecadal near term prediction experiments (up to 2035) with initialized ocean state (WGI Chapter 11). Results from these experiments and analyses of un-initialized simulations show some evidence for the predictability of yearly to decadal averages of temperature both for the global average and for some geographical regions.

The time-mean rate of GMSL rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010, under all the RCP scenarios. [21.3.3] The ocean thermal expansion and glacier melting is *likely* to make the largest contributions to this rise. By the end of the 21st century it's *very likely* that over about 95% of the oceans will undergo sea level rise. The impacts of this sea-level rise, however, will also be a function of local and regional conditions, including coastal subsidence (or coastal uplift) and patterns of development near the coast.

The uncertainties inherent in climate model projections of regional climate changes have not decreased from AR4. [21.3.3] In some cases, the addition of regional forcings (e.g. topography) has increased some uncertainties.

The expanded use of multiple scenario elements beyond that of only climate scenarios still has unresolved issues. [21.5.3] Among these are the model-to-model variability of the integrated assessment models used to generate representative concentration pathways and shared socioeconomic pathways. This variability, and its consequences for impacts and adaptation analyses, or for understanding potential future climates, is largely unexplored.

Climate models continue to produce a range of projected futures where for some variables and locations the sign of projected change may differ from one model to another. [21.5.3] However, in many instances this indicates a lack of significant change compared to the natural variability for that region. The degree to which the model uncertainty can be reduced remains an open question.

Uncertainties of future climate remain centred on uncertainties over future climate forcing from emissions and concentrations, the climate system response to forcing, and the natural internal variability of the climate system. [21.5.3] The likelihood of reducing uncertainty in future emissions and concentrations appears low, and future scenarios are mainly presented as having equal plausibility. Uncertainty in the climate system uncertainty has multiple sources in constrained understanding of the system dynamics, in how the system components are modelled, and in the parameterization of processes.

Downscaling of coarse resolution global climate reconstructions and models has advanced to bring information closer to the temporal and spatial resolution requirements for projecting many regional impacts. [21.5.3] This information remains weakly coordinated, and current results indicate models can have significant errors in their high resolution reconstructions of the current climate.

Hotspots draw attention, from various perspectives and often controversially, to locations judged to be especially vulnerable to climate change. [21.4.4] Hotspots is an approach that has been used to indicate locations that stand out in terms of impacts, vulnerability or adaptive capacity (or all three). The approach exists in many fields and the meaning and use of the term hotspots differs, though their purpose is generally to set priorities for policy action and for further research. In the context of climate change, hotspots have been defined with respect to: climate changes themselves, biodiversity, health and disease, disasters, and food production and food security. Hotspots can be very effective as communication tools, but may also suffer from methodological weaknesses. They are often subjectively defined, relationships between indicator variables may be poorly understood and they can be highly scale-dependent. In part due to these ambiguities, there has been controversy surrounding the growing use of hotspots, particularly in relation to prioritising regions for climate change funding.

Improved regional scale climate information is now available to provide a more coherent picture of past and future regional changes with associated uncertainties. [21.3.3, 21.5.3] More targeted analysis of climate projections for impact assessment studies have been carried out, from which the leading messages to emerge include

- A strong regional variability of projected change is found for surface climate variables. Different indexes combining sets of climate variables and statistics indicate the emergence of various climate change hot-spots at different times in the future. Better process understanding is needed to increase confidence in the identification of climate change hot-spots (i.e. regions in which potential climate change impacts on the environment or different activity sectors can be particularly pronounced or where climate is especially responsive to global change).

- Broad regional patterns of late 21st century temperature and precipitation change projections, as well as changes in temperature and precipitation extremes, from the latest generation GCM simulations (CMIP5) are generally in line with previous projections available in the AR4.
- Preliminary analysis of decadal prediction experiments in the CMIP5 ensemble show that decadal predictability of unforced regional precipitation and temperature patterns over land is very low. Indications of some predictability of ocean temperatures of up to 10 years lead time is however found over some ocean basins
- A larger set of global and regional (both dynamical and statistical) model projections allow a better characterization of uncertainties than in the AR4, and more methods are available to produce probabilistic projections of changes for use in IAV assessment work.
- Projected changes in the oceans, sea level and cryosphere are also consistent, at least qualitatively, with previous estimates from the AR4 and with improved observations of recent past trends. Quantitative values of projected changes may however differ from the AR4 due to the availability of better models and larger ensembles, especially at the regional scale.
- Climate change is expected to substantially affect regional air quality, for example near surface ozone concentrations, however this effect also depends strongly on future emissions.

There is significant new information on many of the physical non-climatic factors, especially those that are components of the new RCPs used in the CMIP5. [21.5.3] Non-climatic factors relevant to assessing a system's vulnerability general involve a complex mix of physical and socio-economic influences. Often these are continually evolving and thus generally only a reference point in time rather than a reference state over a period of time can be defined. Improvements in observations of other factors have also occurred but, as with climate information, in many cases the quality is regionally dependent and there are resolution deficiencies. The literature on characterizing vulnerability on sub-national and regional scales is mixed – but it is clear that there is significant variation in vulnerability due to variability in wealth, income, social factors, and access to governance.

The derivation of the RCP's and the parallel process for scenario development has enabled the climate modeling community to consider explicit mitigation scenarios for the first time in systematic model intercomparisons. [21.5.3] Substantial regional information of economic activity, development trajectories, and emissions are available for analysis, but remain largely unexplored. The RCP's are known not to be unique pathways to the identified radiative forcing targets. Model to model variability of the IAM's used to generate the RCP's is also largely unexplored.

Achieving emission targets without putting a price on carbon emissions from land-use has the potential to lead to very large reductions in forested area, and much higher overall costs for mitigation, compared to meeting the same targets while putting a price on all carbon emissions. [21.5.3] Similarly, substantial regional variation in the availability of technologies exists, but the differences in how these are represented regionally is largely unexplored. A process (shared socioeconomic pathways, SSP's) has been initiated to identify shared assumptions and global scenarios for use in both mitigation and adaptation research. But although progress has been made, the vast majority of the impacts, adaptation, and vulnerability literature since AR4 continues to be based on the SRES.

Bulk transport of products, whether by air, sea or over land, is now highly likely to be a non-trivial contributor to emissions of greenhouse gases and aerosols. [21.4.1] Furthermore, the relocation of manufacturing has transferred net emissions via international trade from developed to developing countries and most developed countries have increased their consumption-based emissions faster than their domestic (territorial) emissions.

Contested definitions and alternative approaches to describing vulnerability to climate change pose problems of interpretating vulnerability indicators. [21.5.1] There are numerous studies that use ndicators to define aspects of vulnerability, quantifying these across regonal units (e.g. by country or municipality), often weighting and merging them into vulnerability indices and presenting them regionally as maps. However, methods of constructing indices are subjective, often lack transparency and can be difficult to interpret. Moreover, indices commonly combine indicators reflecting current conditions (e.g. of socio-economic capacity) with other indicators describing

projected changes (e.g. of future climate or population), and have failed to reflect the dynamic nature of the various variables used as indicators.

The variability of vulnerability across regions, and across subpopulations within regions preclude general statements about the factors that control that variability, and how they might evolve in the future. [21.5.1] Trade and financial flows influence both vulnerability and adaptive capacity, and also the regionalization of emissions. At the same time, international and cross-regional financial instruments are being used to attempt to build adaptive capacity as well as mitigation capacity. Human migration in reaction to climate-driven phenomena, or extreme weather events, is usually within nations, but under some circumstances, can extend across nations. The migration of ecosystems in response to changes in climate emphasizes the need for cross-regional cooperation of conservation and resource management institutions.

21.1. Introduction

The framing of this chapter places the discussion of both global and regional issues in a decision-making context. This context identifies different scales of decisions that are made (e.g. global, international, regional, national) and the different economic or impact sectors that are often the objects of decision-making (e.g. agriculture, water resources, energy).

Within this framing, the chapter then provides three levels of synthesis. First is an evaluation of the state of knowledge of changes in the physical climate system, and the degree of confidence that we have in understanding those changes on a regional basis that is relevant to decision-making. The second is a discussion of the regional context of the sectoral discussions in Part A of Working Group II. The third is to discuss the regional variation revealed in subsequent chapters of Part B. In so doing, the goal is to examine how each regional chapter addresses decision-making issues in similar or different ways, and whether there is commonality of experience among regions that could be useful for decision-making.

Having analyzed similarities and differences among IPCC regions, the chapter then discusses trans-regional and cross-regional issues that affect both human systems (e.g. trade and financial flows) and natural systems (e.g. ecosystem migration). Finally, the chapter evaluates methodologies for assessing regional vulnerabilities and adaptations, impact analyses, and the development and application of scenarios of the future. These evaluations provide guidance for understanding how such methods might ultimately be improved, so that the confidence in research about possible future conditions and consequences might ultimately improve.

21.2. Defining Regional Context

The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather and longer-term climate trends – are assuredly regional or local in their occurrence, character and implications. Explicit recognition of geographical diversity is therefore an imperative for any scientific assessment of anthropogenic climate change. Moreover, the decisions that are or could be taken on the basis of climate change science play out on a range of scales, and the relevance and limitations of information on both biophysical impacts and social vulnerability differ strongly from global- to local-scale, and from one region to another. The following sections emphasize some of the crucial regional issues to be pursued in Part B of this report.

21.2.1 Decision-Making Context

This is the first full IPCC assessment to devote a single part of a report to regional aspects of climate change that cut across topics in all three IPCC Working Groups. Hence, this part of the report attempts to address many of the regional dimensions of the climate change issue that are regarded as relevant to decision making. Naturally, a lot of emphasis is placed on informing national and international climate change policy making, but the demand for information to support practical decision-making has assumed an increasingly sub-national focus. However, while

expeditious use of case studies can provide useful illustrations of local-scale phenomena, geographical comprehensiveness is necessarily ruled out in this assessment. Instead, responsibility for compiling and disseminating local information rests with regional and national experts, while this report seeks to highlight robust examples of these, wherever possible.

A good understanding of the decision-making context is essential to define the type of information on climate change related risks required from physical climate science and impacts, adaptation and vulnerability assessments (e.g. IPCC, 2012a). While the importance of considering the decision-making context is a general issue for all impacts, adaptation and vulnerability assessments (cf. the chapters in Part A), it is especially important in the context of regional and sub-regional issues. Many studies are still driven by global data and assessment methods, whereas there is considerable variation in regional, national and local decision-making contexts, as well as across different groups of stakeholders and sectors. There is a growing body of scientific information on how to provide the most relevant climate risk information to suit specific decision-making processes (e.g., Willows and Connell, 2003; ADB, 2005; Kandlikar *et al*., 2011 decision-making).

Table 21-1 illustrates the range of actors involved in decision-making to be informed by climate information at different scales in different sectors, ranging from international policy makers and agencies, to national and local government departments, to civil society organizations and the private sector at all levels, all the way to communities and individual households. The implications of climate change touch on almost all sectors of society, so the figure illustrates how policy makers face a dual challenge in achieving policy integration – vertically, through multiple levels of governance, and horizontally, across different sectors (Table 21-1). Many of the barriers to effective climate response are to be found in these two dimensions. For instance, in the vertical dimension, while a growing number of European countries have developed national adaptation strategies in recent years, the implementation of adaptation measures at a local level has lagged behind, because responsibility and resources for adaptation at the local level have yet to be properly assigned (Biesbroek *et al*., 2010). In contrast, horizontal integration (policy coherence – Mickwitz *et al*., 2009) often flies in the face of conventional practice, with sectoral policies that are designed to advance social or economic goals (e.g. development of an improved road network) frequently at odds with goals set in other sectors (e.g. environmental targets to limit greenhouse gas emissions or to reduce infrastructural exposure to flood risk). Finally, implicit in the framing of Table 21-1, is the temporal dimension of decision, manifested through their scheduling, cost and ultimate effectiveness. Though this dimension is not shown in Table 21-1, it is a crucial element to consider in interpreting both the types of response options facing decision-makers (for example, contrasting a one-off, long-term major infrastructural investment against multiple, incremental and flexible short-term measures) as well as the information used to inform those decisions.

[INSERT TABLE 21-1 HERE
Table 21-1: Dimensions of the institutions and actors involved in climate change decision-making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decison-making domains are illustrative. Modified and extended from Mickwitz (2009).]

Many climate change risk assessments have traditionally been undertaken either in the context of international climate policy-making (especially the United National Framework Convention on Climate Change – UNFCCC), or by (or for) national governments. In those cases, climate risk information commonly assumes a central role in the decision-making, for instance to inform mitigation policy, or for plans or projects designed specifically to adapt to a changing climate. More recently, increasing attention has been paid to more sector- or project-specific risk assessments, intended to guide planning and practice by a range of actors. In those contexts, climate may often be considered as only one contributor among a much wider set of considerations for a particular decision. In such cases, there is uncertainty about not only the future climate, but also many other aspects of the system at risk. Moreover, while analysts will seek the best available climate risk information to inform the relative costs and benefits of the options available to manage that risk, they will also need to consider the various constraints to action faced by the actors involved.

Some decision-making contexts, such as the design of large infrastructure projects, may require rigorous quantitative information to feed formal evaluations, often including cost-benefit analysis (e.g. PriceWaterHouseCoopers 2010), for more examples see also chapter 17). Others, especially at local level, such as decision-making in traditional

communities, are often made more intuitively, with a much greater role for a wide range of social and cultural aspects, and may benefit much more from experience-based approaches, participatory risk assessments, or story-telling to evaluate future implications of possible decisions (e.g. Van Aalst *et al.,* 2008, World Bank, 2010). Multi-criteria analysis, scenario planning, and flexible decision paths offer options for taking action when faced with large uncertainties or incomplete information, and can help bridge adaptation strategies across scales (in particular between the national and local level).In most cases, an understanding of the context in which the risk plays out, and the alternative options that may be considered to manage it, are not an afterthought, but a defining feature of an appropriate climate risk analysis, which requires a much closer interplay between decision-makers and providers of climate risk information than often occurs in practice (e.g., Cardona *et al.,* 2012; Hellmuth *et al.,* 2010; Mendler de Suarez *et al.,* 2012).

These different decision-making contexts also determine the types of information required, including the climate variables of interest and the geographic and time scales on which they need to be provided. Many climate change impact assessments have traditionally focused on changes over longer time horizons (often out to 2100, though recently studies have begun to concentrate more on mid-century or earlier). In contrast, most decisions taken today have a planning horizon ranging from a few months to about two decades (e.g Wilby et al., 2009). For many such shorter-term decisions, recent climate variability and observed trends are commonly regarded as sufficient to inform adaptation (e.g. Hallegatte, 2009). However, in so doing, there is often scope to make better use of observed climatological information as well as seasonal and maybe also decadal climate forecasts (e.g. Wang *et al*., 2009; Ziervogel *et al*., 2010; Mehta *et al*., 2011; Kirtman *et al*., in prep., HLT, 2011). For longer-term decisions, such as decisions with irreversible long-term implications and investments with a long investment horizon and substantial vulnerability to changing climate conditions, longer-term climate risk information is needed (e.g. Reeder and Ranger, 2010). However, while that longer-term information is often used simply to plan for a best-guess scenario to optimize for most likely conditions, there is increasing attention for informing concerns about maladaptation (Barnett and O'Neill, 2010) and sequencing of potential adaptation options in a wider range of possible outcomes, requiring a stronger focus on ranges of possible outcomes and guidance on managing uncertainties, especially at regional, national and sub-national levels (Hall *et al*., 2012; Gersonius *et al*., 2013).

Section 21.3 summarises different approaches to impacts, vulnerability and adaptation assessment that have been applied at different scales in studies assessed in this volume, paying special attention to information contained in the regional chapters.

21.2.2. Defining Regions

As the preceding discussion implies, the most effective treatment of regional aspects of the observed and projected physical climate, its impacts and response options may frequently be at odds with the scales at which decisions actually need to be made. Earlier attempts by IPCC author teams to reconcile this mismatch are described below.

There has been an evolution in the treatment of regional aspects of climate change in IPCC reports (Table 21-2) from a patchwork of case examples in the First Assessment Report (FAR) and its supplements, through to attempts at a more systematic coverage of regional issues following a request from governments, beginning with the Special Report on the Regional Impacts of Climate Change in 1998. That report distilled information from the Second Assessment Report (SAR) for ten continental scale regions, and the subsequent Third (TAR) and Fourth (AR4) assessments each contained comparable chapters on impacts, adaptation and vulnerability in the Working Group (WG) II volumes. WG I and III reports have also addressed regional issues in various chapters, using different methods of mapping, statistical aggregation and spatial averaging to provide regional information.

[INSERT TABLE 21-2 HERE
Table 21-2: Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SR). Major assessments are subdivided by the three Working Group reports, each described by generic titles.]

Part B of this WG II Fifth Assessment (AR5) is the first to address regional issues treated in all three WGs. It comprises chapters on eight regions plus open oceans. These are depicted in Figure 21-1.

[INSERT FIGURE 21-1 HERE
Figure 21-1: Map showing regions described in chapters 22-30 of Part B (colours) with numbered [26] open polygons defining sub-regions over land used to summarise projected changes in climate in this chapter Note that regional specifications are approximate, as aspects of some regions or territories are treated in more than one chapter. Supplementary material contains more details of chapter assignment (Table S21-1) as well as co-ordinates of the polygons (Table S21-2).]

Some of the main topics demanding a regional treatment are:

- *Climate*, typically represented by sub-continental regions, a scale at which trends in observations tend to be fairly robust, and at which signal:noise ratios for projections from global models may also offer some confidence. While maps are widely used to represent climatic patterns, regional aggregation of this (typically gridded) information is still required to summarise the processes and trends they depict. Examples, including information on climate extremes, are presented elsewhere in this chapter, with systematic coverage of all regions provided in supplementary material. Excerpts from maps produced for an atlas of global and regional climate projections accompanying the WG I report (Collins *et al*., in prep.) can also be found in several regional chapters of this volume. In Figure 21-1, the sub-continental regions used for summarising climate information are overlaid on a map of the nine regions treated in Part B.
- *Other aspects of the climate system*, such as the cryosphere, oceans, sea level, and atmospheric composition, especially given the importance of regional changes, for example, in sea ice cover for navigation, in land movements and local ocean currents that may counter or reinforce global sea level rise, or in air pollution that can be a major regional driver of atmospheric radiative forcing as well as having a confounding effect (often localised) on plant and human health.
- *Climate change impacts* on natural resource sectors, such as agriculture, forestry, ecosystems, water resources and fisheries, which often require a classification of regional types to distinguish contrasting environmental conditions, and the livelihoods and human interventions that accompany them. Here, it is common to classify regions according to biogeographical characteristics (e.g. biomes, climatic zones, physiographic features like mountains, river basins or deltas, or combinations of these).
- *Adaptive capacity*, which is a measure of society's ability to adjust to the potential impacts of climate change, sometimes characterised in relation to social vulnerability (Füssel, 2010),, and typically represented through the use of socio-economic indicators. The regional dimensions of adaptive capacity are often displayed as maps contrasting statistical data collected, modelled or aggregated at the scale of a given administrative unit (national maps with municipal comparisons – O'Brien *et al*., 2006; e.g., global maps showing national comparisons – Füssel, 2010´).
- *Emissions* of greenhouse gases and aerosols and their cycling through the Earth system have a crucial regional expression that requires combining socio-economic data on human activities responsible for anthropogenic emissions with biogeochemical monitoring of material and gas fluxes worldwide. Since these activities are known to be responsible for anthropogenic climate change, and given that national and international policies are being designed to modify human activities, the regional units of most relevance for governments are those that provide comparison between political and economic regional groupings worldwide.
- *Global scenarios* of the major socio-economic, technological and land use drivers that affect anthropogenic emissions as well as influencing societal vulnerability to the impacts of climate change, rely heavily on integrated assessment models (IAMs) of the global energy–environment–socioeconomic system. Quantitative scenarios derived from such models need to be aggregated into regional units of relevance to stakeholders wishing to interpret and apply such scenarios. SRES was the most comprehensive scenario development exercise conducted to date to serve the climate change community, though the scenarios themselves are provided in common only for four world regions. New scenarios are under development by the global research community, and these are being designed to have more regional detail than SRES (Moss *et al*., 2010 – see Box 21-1).
- Finally, *human responses to climate change through mitigation and adaptation* demand both global and regional approaches, as emphasised in the Articles of the UNFCCC and manifest in international financing to support climate policy (not only through UNFCCC-related financial mechanisms, but also via bilateral development agencies and multilateral development banks). However, governments require access to

useable knowledge that can be applied at national and local scales. That is a regional challenge beyond the scope of an IPCC report alone, but for which these assessments should provide the appropriate context.

These give a flavour of the different approaches that are commonly employed in specifying regional units of analysis. Detailed examples of these will be referred to throughout this chapter and the regional chapters that follow. Some of the more important international political groupings of countries and territories are described and catalogued in supplementary material.

_____ START BOX 21-1 HERE _____

Box 21-1. A New Framework of Global Scenarios for Regional Assessment

The major socio-economic driving factors of future emissions and their effects on the global climate system were characterized in the TAR and AR4 using scenarios derived from the IPCC Special Report on Emissions Scenarios (SRES – IPCC, 2000). Scenarios were developed in a linear process, whereby socio-economic scenarios were constructed to represent key drivers of emissions, model estimates of emissions were converted to atmospheric concentrations of greenhouse gases and aerosols that in turn were used as input to climate models for simulating the climate response to the forcings. Finally, IAV assessments were conducted using combinations of the socio-economic, atmospheric composition, climate and related projections such as land cover and sea level, downscaled to the region of interest. More recently a new approach to developing climate and socio-economic scenarios has been adopted in which atmospheric concentrations were developed first (Representative Concentration Pathways or RCPs – Moss et al., 2010), thereby allowing climate modeling work to proceed much earlier in the process. Different possible Shared Socio-economic Pathways (SSPs) were to be determined later, recognizing that more than one socio-economic pathway can lead to the same concentrations of greenhouse gases and aerosols.

Four different RCPs were developed, corresponding to four different levels of radiative forcing of the atmosphere by 2100 relative to pre-industrial levels, expressed in units of Wm^{-2}: RCP 8.5, 6.0, 4.5, and 2.6 (van Vuuren et al., 2012). These embrace the range of scenarios found in the literature, and all except RCP 8.5 also include explicit stabilization strategies, which were missing from the SRES set.

In addition, five SSPs have been proposed, representing a wide range of possible development pathways (van Vuuren et al., submitted). An inverse approach is applied, whereby the SSPs are constructed in terms of outcomes most relevant to IAV and mitigation analysis, depicted as challenges to mitigation and adaptation (Chapter 19, Figure 19-x). Narrative storylines for the SSPs have been outlined (O'Neill et al., submitted) and preliminary quantifications of the socio-economic variables are underway (O'Neill et al., 2012). Priority has been given to a set of *basic* SSPs with the minimum detail and comprehensiveness needed to provide inputs to IAV and integrated assessment models, primarily at global or large regional scales. Building on the basic SSPs, a second stage will construct *extended* SSPs, designed for finer-scale regional and sectoral applications (O'Neill et al., submitted).

An overall scenario architecture has been designed for integrating RCPs and SSPs (Kriegler et al., 2012; van Vuuren et al., submitted; van Vuuren et al., 2012), for considering mitigation and adaptation policies using Shared Policy Assumptions (SPAs – Kriegler et al., submitted) and for providing relevant socio-economic information at the scales required for IAV analysis (van Ruijven et al., submitted). Additional information on these scenarios can be found in other chapters of this report (Chapter 1, Section 1.1.3, Chapter 19, Box 19-3) and elsewhere in the assessment (Blanco et al., in prep.; Collins et al., in prep.; Kunreuther et al., in prep.). However, due to the time lags that still exist between the generation of RCP-based climate change scenarios, and the development of SSPs, few of the IAV studies assessed in WG II actively use these scenarios. Instead, most of the scenario-related studies in the assessed literature still rely on the SRES. As such, for purposes of comparison it can be instructive to attempt an approximate mapping of the SRES scenarios onto the new scenario framework (see Figure 1 – Carter et al., submitted). On the horizontal axis, SRES socio-economic characteristics are matched to those of SSPs grouped according to low, medium or high challenges for adaptation (O'Neill et al., submitted; van Vuuren et al., 2012). On the vertical axis, mapping of SRES onto the RCPs is based on radiative forcing by 2100 (chapter 1, this volume). Cells in the matrix indicate SRES mappings that coincide on both axes. Note that no SRES scenarios result in forcing as low as RCP

2.6, though SRES mitigation scenarios have been applied in a few climate model experiments (e.g. the E1 scenario – Johns et al., 2011).

[INSERT BOX 21-1 FIGURE HERE
Box 21-1 Figure Caption: Approximate mappings of the SRES scenarios onto the new SSP/RCP framework (for details, see text). After Carter et al. (submitted).]

_____ END BOX 21-1 HERE _____

21.2.3. Introduction to Methods and Information

There has been significant debate about the definitions of key terms (Janssen and Ostrom, 2006), such as vulnerability (Adger, 2006), adaptation (Stafford Smith et al,. 2011), adaptive capacity (Smit and Wandel, 2006) and resilience (Klein et al., 2003). One explanation is that the terms are not independent concepts, but defined by each other, thus making it impossible to remove the confusion around the definitions (Hinkel 2011). The differences in the definitions is based on the different entry points for looking at climate change risk (IPCC, 2012). Figure 21-2 shows four possible entry points to adaptation science, policy and practice (based on Hinkel et al, submitted). Each of these attracts a separate set of actors and researchers and relies on different sets of methods and tools.

[INSERT FIGURE 21-2 HERE
Figure 21-2: Entry points for adaptation science, policy, and practice (based on Hinkel et al, submitted).]

Table 21-3 shows two ways to think about vulnerability, demonstrating that different objectives (e.g., improving well being and livelihoods or reducing climate change impacts) lead to different sets of questions being asked. This results in the selection of different methods to arrive at the answers. The two approaches portrayed in the middle and right hand columns of Table 21-3 have also been characterised in terms of top-down (middle column) and bottom-up (right column) perspectives, with the former identifying physical vulnerability and the latter social vulnerability (Dessai and Hulme 2004). In the middle column, the development context is the starting point (i.e., social vulnerability), on top of which climate change occurs. The task is then to identify what changes are needed in the development pathways in order to reduce vulnerability to climate change. On the right, the climate change impacts are the starting point for the analysis, revealing that people and/or ecosystems are vulnerable to climate change. One of the differences is a difference in time-frames, where a climate change focussed approach tends to look to the future to see how to adjust to expected changes, whereas a vulnerability focussed approach is centred on addressing the drivers of current vulnerability. A similar approach is described by McGray et al (2009).

[INSERT TABLE 21-3 HERE
Table 21-3: Two possible entry points for thinking about vulnerability to climate change (adapted from Füssel 2007).]

The information assessed in this chapter stems from different entry points, framings and conceptual frameworks for thinking about risk. They merge social and natural science perspectives with transdisciplinary ones. There is no single 'best' conceptual model: the approaches change as scientific thinking evolves. The IPCC itself is an example of this: IPCC SREX presented an approach that has been adjusted and adapted in Chapter 19 of this volume. Chapter 2 describes other conceptual models for decision making in the context of risk. While this diversity in approaches enriches our understanding of climate change, it can also create difficulties in comparisons. For instance, findings that are described as vulnerabilities in some studies may be classified as impacts in others; lack of adaptive capacity in one setting might be described as social vulnerability in another.

21.3. Synthesis of Key Regional Issues

This section highlights regional distributions of key issues and briefly considers related methodological issues. It focuses on material contained in the regional chapters of this volume, and considers the advantages or disadvantages

of analysing information about vulnerability, impacts and adaptation at a global or large-region scale. The value of taking a regional and global approach to vulnerability, impacts and adaptation is the ability to compare and contrast sub-regions. For example, regionally distributed impacts information can be assessed in conjunction with examinations of regional political economies to provide a context for understanding implications of impacts. Underpinning such analyses is an appreciation of ongoing and projected regional changes in the physical climate system.

Determining what belongs to a region or sub-region is addressed in 21.2, but deserves mention in the context of how to represent causal links of a geographical nature across regions and within them. Although climate change will affect different places in different ways, there will be spillover effects from one location to the next (Government Office for Science, 2011). For instance, a spillover effect occurs when there is a significant drought in a food-exporting country leading to food scarcity or insecurity in other countries (Sasson, 2012).

An examination of the nine regional chapters included in this volume of AR5 indicates that there is diversity in knowledge about climate change and its vulnerabilities, impacts and adaptation responses among and within different regions of the world. Research findings available for different global regions vary in terms of robustness, quantity, scope, and regional representativeness. With a substantial component of climate research devoted to global modelling, large scale aspects of regional climate are gradually becoming better understood over time. However, advances in knowledge about the finer details of regional climate change and its manifestations, have been more uneven, due in part to regional differences in data availability, resources and capacity.

Most regions have been conducting impacts studies for longer than they have been concerned with adaptation, so there is more region-specific information available on impacts. Some of the general issues that can be identified include the generality of much adaptation knowledge, and the limited amount of region-generated knowledge; differences in knowledge about social versus ecological vulnerability and impacts; and the difficulty of making general statements about regions that have high variability in terms of national poverty levels and adaptive capacity, such as Asia. The review below is limited to the literature that has been assessed by the regional chapters, and aims to highlight key issues to demonstrate either similarities or differences among regions. When regional chapters have omitted to describe these issues in their chapters, the assumption is that insufficient literature exists to provide evidence for any statement, but the information could also have been omitted for lack of space or because other issues are more relevant.

Aside from analyses that are conducted purely out of academic interest, most of the IAV studies assessed in this volume have been undertaken to serve a specific target audience. Thus, they can be regarded as providing information that might potentially be useful for decision-makers operating across a variety of sectors and levels of organisation (cf. Table 21-1). Here, an attempt is made to organise this information according to the broad research approach applied, distinguishing impacts and vulnerability approaches from adaptation approaches. Studies are then categorised according to scales of application ranging from global to local, which in turn helps to define the types of target audience intended. Table 21-4 has been constructed using these criteria, and is populated with examples of IAV studies drawn from other chapters in the volume as well as from a broader literature. This configuration then allows for an approximate matching of items in this Table with some of the dimensions of decision-making depicted in Table 21-1.

[INSERT TABLE 21-4 HERE

Table 21-4: Dimensions of assessments of impacts and vulnerability and of adaptation drawn upon to serve different target audiences (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to the original studies and to the chapters in which they are cited. Aspects of some of the studies in this table are also alluded to in section 21.5.]

The following sub-sections offer a brief synopsis of the approaches being reported in the different regional chapters, starting with impacts and vulnerability studies and then moving to adaptation studies. Table 21-4 serves as a rough template for organsing this discussion. Section 21-3-3 then provides an analysis of advances in understanding of the

physical climate system for the different regions covered in chapters 22-30, introducing new regional information to complement the large-scale and process-oriented findings presented by Working Group I.

21.3.1. Vulnerabilities and Impacts

21.3.1.1. Observed Impacts

The first step taken by many researchers undertaking climate change impact assessments, before attempting to estimate future impacts, is to investigate how past and ongoing variations in climate may have affected a given exposure unit. This is also the approach adopted in many of the regional chapters in this volume, and there is also a separate chapter in Part A of the volume (chapter 18) dedicated to this topic

The evidence linking observed impacts on biological, physical and (increasingly) human systems to recent and ongoing regional climate changes has become more compelling since the AR4 (see chapter 18). One reason for this is the improved reporting of published studies from hitherto under-represented regions of the world, especially in the tropics (Rosenzweig and Neofotis, 2013). That said, the disparity is still large between the copious evidence being presented from Europe and North America, as well as good quality data emerging from Australasia, polar regions, many ocean areas and some parts of Asia and South America, compared to the much sparser coverage of studies from Africa, large parts of Asia, central and South America and many small islands. On the other hand, as the time series of well-calibrated satellite observations become longer in duration, and hence statistically more robust, these are increasingly providing a near global coverage of changes in surface characteristics such as vegetation, hydrology, and snow and ice conditions that can usefully complement or substitute for surface observations (see Table 21-2 and chapter 18 for examples). Changes in climate variables other than temperature, such as precipitation. evapotranspiration and CO_2 concentration, are also being related to observed impacts in a growing number of studies (Rosenzweig and Neofotis, 2013). For example, ecosystem responses would be expected to follow closely any long-term trends in precipitation and water availability in some tropical and sub-tropical regions, and although trends are often confounded by modes of climatic variability such as ENSO, some evidence for precipitation-related impacts is reported from Australia (in chapter 26) and southern South America [chapter 27).

Other regional differences in observed changes worth pointing out include trends in relative sea level, which is rising on average globally (Church *et al.*, in prep.), but displays large regional variations in magnitude, or even sign, due to a combination of influences ranging from El Niño/La Nina cycles to local tectonic activity, making general conclusions about ongoing and future risks of sea level change very difficult to draw across diverse regional groupings such as small islands (see chapter 29). There are also regional variations in another ongoing effect of rising CO_2 concentration – ocean acidification, due to temperature dependence of the carbon flux to the ocean, with cooler, high latitude oceans experiencing the most rapid fluxes (chapter 30). Calcifying organisms are expected to show responses to these trends in future, though few recent trends are apparent that can be attributed to acidification effects alone. Finally, although problematic to disentangle from other potential explanatory factors, there is also mounting evidence that human adaptation is occurring as an autonomous response to ongoing climate change in some regions (e.g. draining glacial lakes to ameliorate the risk of flash flooding triggered by accelerated melting, sowing crops earlier in the spring to exploit warmer conditions, or changing reservoir operations to mitigate floods). These issues are touched on in chapters 18, 23, 25.

21.3.1.2. Future Impacts and Vulnerability

21.3.1.2.1. Impact models

The long-term monitoring of environmental variables, as well as serving a critical role in the detection and attribution of observed impacts, also provides basic calibration material used for the development and testing of impact models. These include process-based or statistical models used to simulate the biophysical impacts of climate on outcomes such as crop yield, forest productivity, river runoff, coastal inundation or human mortality and morbidity (see chapters 2-7; 11). They also encompass various types of economic models that can be applied to

evaluate the costs incurred by biophysical impacts (see, for example, chapters 10 and 17). There are also integrated assessment models (IAMs), Earth System Models, and other more loosely linked integrated model frameworks that might incorporate several different biophysical impacts as well as economic and perhaps other processes (e.g. climate, land use change, global trade) and the various interactions and feedbacks between them. For descriptions of these, see chapter 17 and (Flato *et al*., in prep.).

21.3.1.2.2. Vulnerability mapping

A second approach to projecting potential future impacts, is to construct vulnerability maps. These usually combine information on three components: exposure to a hazard – commonly defined by the magnitude of climate change, sensitivity to that hazard -- the magnitude of response for a given level of climate change, and adaptive capacity – describing the social and economic means to withstand the impacts of climate change (IPCC, 2001). Key indicators are selected to represent each of the three components, which are typically combined into a single index of vulnerability. Indicators are usually measured quantities taken from statistical sources (e.g. income, population), or have been modelled separately (e.g. key climate variables). Vulnerability indices have received close scrutiny in several recent reviews (Füssel, 2010; Hinkel, 2011; Malone and Engle, 2011; Preston *et al*., 2011), and a number of global studies have been critiqued by Füssel (2010).

A variant of vulnerability mapping is risk mapping. This commonly identifies a single indicator of hazard (e.g. a level of flood expected with a given return period), which can be mapped accurately to define those regions at risk from such an event (e.g. in a flood plain). Combined with information on changing return periods of such events under a changing climate would enable some estimate of altered risk to be determined.

21.3.1.2.3. Experiments

A final approach for gaining insights on potential future impacts, concerns physical experiments designed to simulate future altered environments of climate (e.g. temperature, humidity and moisture), and atmospheric composition (e.g. CO_2, surface ozone and sulphur dioxide concentrations). These are typically conducted to study responses of crop plants, trees and natural vegetation,. using open top chambers, greenhouses or free air gas release systems (Craufurd *et al*., 2013).

21.3.1.2.4. Scale issues

Impact models operate at a range of spatial and temporal resolutions, and while their outputs are sometimes presented as fine resolution maps, key model findings are rarely produced at the finest resolution of the simulations (i.e. they are commonly aggregated to political or topographic units of interest to the target audience, e.g. watershed, municipality, national or even global). Aggregation of data to coarse-scale units is also essential for allowing comparison of outputs from models operating at different resolutions, but it also means that sometimes quite useful detail may be overlooked when model outputs are presented at the scale of the coarsest common denominator. Conversely, if outputs from impact models are required as inputs to other models, the outputs may need to be harmonized to a finer grid than the original data. In such cases, downscaling methods are commonly applied. This was the case, for example, when providing spatially explicit projections of future land use from different IAMs for climate modellers to apply in the CMIP-5 process (see Box 21-1 – Hurtt *et al*., 2011). It is also a common procedure used in matching climate model outputs to impact models designed to be applied locally (e.g. over a river basin or an urban area).

Even if the same metrics are being used to compare aggregate model results (e.g. developed versus developing country income under a given future scenario) estimates may have been obtained using completely different types of models operating at different resolutions. Moreover, many models that have a large-scale coverage (e.g. continental or global) may nonetheless simulate processes at a relatively fine spatial resolution, offering a potentially useful source of spatially explicit information that is unfamiliar to analysts working in specific regions, who may defer to

models more commonly applied at the regional scale. Examples include comparison of hydrological models with a global and regional scope (Todd *et al*., 2011) and bioclimatic models of vascular plant distributions with a European and local scope (Trivedi *et al*., 2008). Vulnerability mapping exercises can also be undermined by the inappropriate merging of indicator datasets that resolve information to a different level of precision (e.g. Tzanopoulos *et al*., 2013). There is scope for considerably enhanced cross-scale model intercomparison work in the future, and projects such as AgMIP (Rosenzweig *et al*., 2013) and ISI-MIP (Schiermeier, 2012, – see section 21.5) have provision for just such exercises.

21.3.2. Adaptation

Although a large portion of adaptation knowledge, for instance, is based on conclusions from case studies in specific locations, the conceptual findings are typically applied globally. Much of this theory on adaptation guides understandings in the different regions. This is especially the case for developing regions. Thus, regional approaches to adaptation vary in their degree of generality. One of the most striking differences between regions in terms of adaptation is the extent to which it has been studied and implemented. Australia and Europe have invested heavily in research on adaptation, and the result is a rich body of literature published by local scientists. The ability to advance in adaptation knowledge may be related to the amount and quality of reliable climate information, the lack of which has been identified as a constraint to developing adaptation measures in Africa. Many case studies, especially of community-based adaptation, stem from Asia and Africa, but the majority of this work has been undertaken and authored by international non-governmental organisations, frequently featuring their own project work, as well as by non-local researchers. In Africa, most adaptation work is considered to be pilot, and seen as part of learning about adaptation, although there has been significant progress since the AR4.

Most regional chapters report lags in policy work on adaptation. While most European countries have adaptation strategies, few have been implemented. Lack of implementation of plans is also the case for Africa. In North, Central and South America, adaptation plans are in place for some cities. In Australasia, there are few adaptation plans. At the same time, civil society and local communities have the opportunity to play a role in decision making about adaptation in Europe and Asia. In Africa, social learning and collective action are used to promote adaptation. Adaptation is observed as mostly autonomous (spontaneous) in Africa, although socio-ecological changes are creating constraints for autonomous adaptation. There is a disconnect in most parts of Africa between policy and planning levels. In the case of UNFCCC-supported activities, such as National Adaptation Programmes of Action, few projects from the African and Asian least developed countries have been funded, thus limiting the effectiveness of these investments. Several chapters (Africa, Europe, North America, Central and South America and Small Islands) explicitly point out that climate change is only one of multiple factors that affect societies and ecosystems and drives vulnerability or challenges adaptation.

Some chapters (Polar Regions, North America, Australasia) emphasise the challenges faced by indigenous peoples and communities in dealing with climate change. Although they are described as having some degree of adaptive capacity to deal with climate variability, shifts in lifestyles combined with a loss of traditional knowledge leave many groups more vulnerable to climate change. Also, traditional responses have been found to be maladaptive because they are unable to adjust to the rate of change, or the broader context in which the change is taking place, as seen in the Arctic. In response to changing environmental conditions, people are taking on maladaptive behaviour – for instance, by going further to hunt because of changed fish-stocks and thus exposing themselves to greater risk, or changing to different species and depleting stocks. The limits to traditional approaches for responding to changing conditions has also been observed in several Small Island States.

Most populated regions have experience with adaptation strategies in agriculture, where exposure to the impacts of climate variability over centuries provides a starting point for making adjustments to new changes in climate. Water and land use management strategies stand out in the literature in common across all of the main continental regions.

The link between adaptation and development is explicit in Africa, where livelihood diversification has been key to reducing vulnerability. At the same time, there is evidence that many short-term development initiatives have been responsible for increasing vulnerability. Other chapters mention constraints or barriers to adaptation in their regions.

For example, the low priority accorded to adaptation in parts of Asia, compared to more pressing issues of employment and education, is attributed in part to a lack of awareness of the potential impacts of climate change and the need to adapt, a feature common to many regions. All developing regions cite insufficient financial resources for implementing adaptation as a significant limitation.

21.3.3. Regional Aspects of the Physical Climate System

This section is intended to provide a summary assessment of regional climate information, particularly regarding cross regional aspects and new emerging knowledge since the AR4, to place the regional chapters in a broader context. It is not intended to provide a detailed region-by-region assessment of information, which can be found in the WGI Chapter 14, the WGI Atlas and the WGII regional chapters. Also, as noted in 21.2.2 there are many different ways in which regions can be defined. However, many of these regional definitions are relevant to decision making and so generating climate change information for such regions is relevant to climate policy. This issue is explored using the example of African economic regions in Box 21-2. Similarly some emphasis is also given to material deriving from dynamical and statistical downscaling work which is often of greater direct relevance for IAV applications than coarser resolution global climate model data.

_____ START BOX 21-2 HERE _____

Box 21-2. Developing Regional Climate Information Relevant to Political and Economic Regions

In most world regions, countries form political and/or economic groupings and coordinate activities within these groups with stated aims such as furthering the interests of the constituent nations and their peoples. Such groupings provide a natural forum for coordinating action on transboundary issues within their region or responding to influences external to it. Climate is an important factor in the economies of many nations and the lives of their peoples and is well understood to have both transboundary dimensions and to involve remote influences. This has long been recognised, with national and regional weather-forecasting being highly dependent on globally coordinated activities, more recently with the advent of the WMO-sponsored Regional Climate Outlook Forums (Ogallo et al., 2010) and Global Framework for Climate Services (Hewitt et al., 2012). These links are also being made regionally. For example, the Intergovernmental Authority on Development (IGAD) of the countries of the Greater Horn of Africa (GHA) recognizes that the region is prone to extreme climate events such as droughts and floods which have severe negative impacts on key socio-economic sectors in all its countries. In response it has set up the IGAD Climate Prediction and Applications Centre (ICPAC) to provide and support application of early warning and related climate information for the management of climate-related risks (for more details see http://www.icpac.net/). As socio-economic factors are important contributors to both the vulnerability and adaptability of human and natural systems, it clearly makes sense to summarise and assess available climate and climate change information for these regions as it will be relevant to policy decisions taken within these groupings on their responses to climate change.

The accompanying figure presents summary climate change information for 5 political/economic regions covering much of Africa. These are the Common Market for Eastern and Southern Africa (COMESA6), the Economic Community of Central African States (ECCAS), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC) and the Arab Maghreb Union (UMA). Each graph shows observed7 and simulated variations in past and projected future annual average temperature and precipitation. Generally the observed regional temperature variations reflect global changes, with warming from 1901 to 1940, followed by a relatively stable period until 1970 and then steady warming thereafter. Consistent with simulations available for the AR4 (Christensen et al. 2007), the observed warming is contained within the envelope of the simulations of global climate models driven with observed changes in all known external drivers (pink band) in all five regions. The 1901-1940 warming in these simulations is partly distinguishable from what would have been expected if anthropogenic activities had not interfered with the climate, as estimated by simulations with observed changes in natural external drivers only (blue band). In all five regions there is a distinct difference by the beginning of the 21st century, which is projected to continue to widen if emissions broadly follow the RCP4.5 or RCP 8.5 emissions pathways (light blue and red bands). In contrast, precipitation has generally remained steady, relative to

its year-to-year variability, without major changes driven by anthropogenic emissions in either the past or future as estimated from the climate model simulations. Exceptions are an observed drying over ECOWAS between the 1960s and 80s (Greene et al. 2009, Hoerling et al. 2006) and a simulated drying of about 15% over the 150-year period over UMA. It should also be noted that, unlike temperature, observed precipitation variability sometimes lies outside the envelope of the simulations from the models, which is consistent with the simulations representing precipitation effectively averaged over larger areas than is represented by the sparse station data underpinning the observed estimates.

[INSERT BOX 21-2 FIGURE HERE
Box 21-2 Figure Caption: Observed and simulated variations in past and projected future annual average precipitation and temperature over five African regions, Common Market for Eastern and Southern Africa (COMESA), the Economic Community of Central African States (ECCAS), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC) and the Arab Maghreb Union (UMA). Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations, taken from the CMIP5 archive (Taylor et al. 2012), driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30) and by two of the RCM emissions/ concentrations scenarios (van Vuuren et al., 2011), "RCP4.5" (68) and "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. The regions are described in Chapter 22 (section 22.1.2) but the COMESA region labelled here covers COMESA north and includes Rwanda, Uganda, and Kenya. Precipitation is included for land territories only, while temperature is included for both land and exclusive economic zone territories. The observational datasets used are GISTEMP (Hansen et al. 2010), HadCRUT3 (Brohan et al. 2006), and MLOST (Smith et al. 2008) for temperature, and CMAP (Xie and Arkin 1997), CRU TS 3.10 (Mitchell and Jones 2005), GPCP v2.2 (Adler et al. 2003), and PRECL (Chen et al. 2002) for precipitation. These suffer in some areas from sparse monitoring coverage.]

The information presented here is illustrative of an approach to presenting a simple summary of observed and projected or predicted climate changes for political/economic regions. The graphs convey important information on the ability of the models to reproduce the observed trends in temperature, that they simulate significantly lower temperatures without the anthropogenic forcings and how future temperatures under typical business as usual emissions paths will continue to rise. The main messages on precipitation are that for most regions the models project that future variations in the annual average will be similar to those simulated for the past and that the models may not capture all of the observed precipitation variability. Without further refinement, this information would suggest that future precipitation scenarios should be significantly informed by the past observed variability. However, at least two additional factors should be taken into account. The first is that these results do not convey information on trends or projected changes in precipitation on seasonal or shorter time-scales . Secondly, theoretical and model evidence indicates that it is not unreasonable to expect that in a warming climate many regions could experience changes in precipitation variability and extremes even with no changes in the average (Allen and Ingram, 2002).

_____ END BOX 21-2 HERE _____

Understanding the confidence that can be placed in climate information used in assessing climate vulnerability and impacts and decision making on adaptation is of crucial importance. This information is relevant and used over a very wide range of scales and it comes with a similarly wide range of confidence. Using a similar classification of spatial scales to that presented in Table 21-4, Table 21-5 provides a summary overview of the levels of confidence that are seen in two of the basic climate variables of relevance, surface temperature and precipitation. This information is drawn from the extensive assessment and supporting literature from the IPCC SREX report, the AR5 WG1 report and some discussion of relevant methodologies and related issues and results are also presented in section 21.5.

[INSERT TABLE 21-5 HERE
Table 21-5: Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to

Very Low (VL). Reliability of information on past climate depends on the availability and quality of observations and in general is higher for temperature as it is easier to observe and a temperature observation at a given location is more representative of temperatures in the surrounding areas than a precipitation observation. In the case of future climate change, which relies on using models of the climate system run into the future, reliability depends on the ability of these models to simulate well the processes that lead to these changes. Again, information on temperature is generally more reliable but this is due to there being more confidence in our ability to simulate the past changes in temperature and our understanding of the processes that cause these changes than is the case for precipitation.

There are significant variations in the reliability of past and future climate information at different temporal and spatial scales, in general at finer scales the information tends to be less reliable given the need for either a greater density observations or models maintaining accuracy at high resolutions. Also, there are significant geographical variations, again the root cause being different for information on past climate than on future climate change. For past climate observation availability and quality is again key and in many regions, especially for precipitation, there are issues with either or both. For future climate change, data availability is less of an issue with the advent of large ensembles of climate model projections but quality can be a significant problem in some regions where the models perform poorly and there is little confidence that the processes driving the projected changes are accurately captured. [Table is an incomplete placeholder pending more complete information from WG1 and other sources]]

In a regional context, the results developed by the AR5 WG1 Chapter 14, Regional Phenomena, are particularly relevant including their evaluation of confidence in models' ability to simulate temperature, precipitation and phenomena together with an assessed implication for the general level of confidence in projections for 2080-2099 of regional temperature and precipitation (Table 21-6).

[INSERT TABLE 21-6 HERE
Table 21-6: Placeholder for a table to be derived from the AR5 WG1 Ch14 table (still in development by WG1) evaluating confidence in GCM simulations and projections of temperature and precipitation and linked regional climate phenomena currently being finalised for the final draft of that chapter.]

21.3.3.1. Atmosphere and Land Surface

21.3.3.1.1. Observed changes and attribution of causes

New estimates of global surface air temperatures for the period of 1901-2010 give an estimated warming of about 0.8 C, and about 0.5 C for the period 1979-2010, when estimated by a linear trend, while the warming for the period 1986-2005 (reference period) compared to 1886-1905 is 0.66 +/- 0.06. Positive annual temperature trends are found over most land areas, particularly since 1979, except regions of central-northern Australia and central western South America (WGI Chapter 2). Relatively large trends have occurred over Europe, the Sahara and middle East, central and northern Asia.

Confidence in global precipitation estimates is low to medium due to incompleteness of data, however when all land areas are filled in using reconstruction methods, land precipitation shows little change since 1900, in contrast to the AR4 assessment of a small increasing trend. The NH mid to high latitudes show an increasing trend, although confidence is also low due to incompleteness of data. Observed precipitation trends show a high degree of spatial and temporal variability, with the occurrence of both positive and negative values (WGI Chapter 2).

Improved detection and attribution methods have shown that it is *extremely likely* that human activities have caused most of the global warming (more than 50%) since the 1950s and that this warming is not due to internal variability alone. The human influence on warming is *likely* over every inhabited continent (there are insufficient data to make an assessment over Antarctica). It is also *likely* that the human influence has altered sea level pressure patterns and related circulations. Attribution of changes in hydrological variables is less confident due to the lack of data though a human influence on zonal patterns of global and on high northern latitude precipitation changes has been detected (WGI Chapter 10).

21.3.3.1.2. Long-term projections

Analyses of the CMIP5 ensembles have shown that, in general, the mean temperature and precipitation change patterns are similar to those found for CMIP3, with a pattern correlation between CMIP5 and CMIP3 ensemble mean late 21st century change greater than 0.9 for temperature and greater than 0.8 for precipitation (WGI Chapter 12). This implies that the regional characteristics of change in the CMIP5 ensemble lead to conclusions generally consistent with those found in the AR4. Given the increased comprehensiveness and higher resolution of the CMIP5 models this adds an element of robustness to the projected changes.

Some of the main characteristics of the projected late 21st century temperature and precipitation changes derived from the CMIP5 ensemble can be broadly summarized as follows (from WGI Chapter 12 and the Atlas) with further details provided in Box 21-3 and accompanying supplementary material.

Temperature

Global-mean surface temperatures for 2081–2100 (relative to 1986–2005) will *likely* be (5–95% range of the CMIP5 models) : 0.2–1.8°C (RCP2.6), 1.0–2.6°C (RCP4.5), 1.3–3.2°C (RCP6.0), 2.6–4.8°C (RCP8.5).

Changes in global land surface air temperature exceed changes in global mean surface air temperature with continental interiors show the largest changes (Figure 21-3). Regions that exhibit relatively high temperature changes (often 50% or more larger than the global mean) are high latitude NH land areas and the Arctic (especially in DJF), Central North America, portions of the Amazon, Mediterranean, and Central Asia in JJA.

[INSERT FIGURE 21-3 HERE
Figure 21-3. CMIP5 ensemble median ratio of local:global average temperature change in the period 2070-2100 relative to 1961-90 under the RCP8.5 emissions/concentrations scenario. The values are displayed on a common 2.5ºx3.75º grid onto which each models' data were regridded and they were calculated as follows: (i) for each model calculate the local change between 1961-90 and 2070-2100 at each grid cell and divide by the global average change over the same period; (ii) identify the median value across the ensemble at each grid cell.]

Precipitation

Changes in precipitation are regionally highly variable, with many areas projected to experience positive change and others exhibiting negative changes (Box21-3). The high latitudes will *very likely* experience greater amounts of precipitation, many mid-latitude arid and semi-arid regions will *likely* experience reduced precipitation, many moist mid-latitude regions will *likely* experience increased precipitation (AR5 WG1 Ch 12).

Basic information on observed historical changes and projected 21st century changes by the CMIP5 ensemble is presented in each of the following regional chapters, and Box 21-3 provides a description of this material.

_____ START BOX 21-3 HERE _____

Box 21-3. Summary Regional Climate Projection Information

To provide some context on observed and future climate changes relevant to the risks associated with climate change vulnerability and impacts and the decision-making on adaptations being planned and implemented in response to these risks summary figures on observed and projected changes in temperature and precipitation are presented in the following regional chapters. These figures show observed changes in annual average surface air temperature and precipitation over the inhabited continental regions for 1986-2005 compared to 1906-1925 and then projections of these annual average variables under two future emissions/concentrations scenarios (RCP 4.5 and 8.5) and two time periods (2046-2065 and 2081-2100, compared to 1986-2005). An example of one of these figures is

given below for Africa (Figure 1). Observed changes are displayed when significant (see details in figure caption below)

[INSERT BOX 21-3 FIGURE 1 HERE

Box 21-3 Figure 1 Caption: Observed and projected changes in annual average temperature and precipitation over Africa. The observations are taken from the CRU TS 3.1 dataset (Harris et al., 2012) and the projections from the CMIP5 multi-model archive (Taylor et al. 2012). Projected changes are shown for the mid-21st century (2046-2065) and the late-21st century (2081-2100) from a baseline period of 1986-2005 under the RCP 4.5 and 8.5 emissions/ concentrations scenarios (van Vuuren et al., 2011). For the observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through to 1925. For the CMIP5 projections, four classes of results are displayed:

1) White indicates areas where for >66% of models the change in annual average precipitation is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions more than 2/3 of models show no significant change (using this measure of significance) in annual average precipitation. However, note that this does not imply no significant change in precipitation averaged over seasonal or shorter time-scales such as months to days.
2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation but less than 2/3 agree on whether annual average precipitation will increase or decrease.
3) Colors with circles indicate the change in annual average precipitation averaged over all models in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation and more than 2/3 agree (but less than 90%) agree on whether annual average precipitation will increase or decrease.
4) Colors without circles indicate the change in annual average precipitation averaged over all models in areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether annual average precipitation will increase or decrease.

For models which have provided multiple realizations for the climate of the recent past and the future, results from each realisation are first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated.]

These figures provide a very broad overview of the projected regional climate changes but in dealing with only annual averages they are not able to convey any information about projected changes in seasonal or shorter timescales. In addition, they are derived solely from the CMIP5 GCMs and do not display any information from the CMIP3 database which is still very relevant to the IPCC WG2 as CMIP3 data are widely used in many of the studies assessed within the AR5 WG2 report. To provide extra context on projected future climate changes which deals with these issues two additional sets of example figures are presented here which display temperature and precipitation changes at the seasonal and daily timescale.

Projected seasonal changes are displayed as area averages over the regions defined in the IPCC SREX report, “Managing the risks of extreme events and disasters to advance climate change adaptation” (IPCC 2012), and compare these for the four RCP scenarios and three of the SRES scenarios (Figure 2). In this example provided for the SREX regions which lie in Central and South America (see Figure 21.1 for their geographical ranges), regional average changes in temperature and precipitation for the period 2071-2100 compared to a baseline of 1961-1990 are plotted for the four standard three months seasons with each CMIP3 or CMIP5 projected change represented by a symbol. (Thirty year periods were chosen for consistency with the figures displayed below showing changes in daily temperatures and precipitation.) Symbols showing the CMIP3 model projections are all grey but differ in shape depending on the driving SRES concentrations scenario and those showing the CMIP5 projections differ in colour depending on the driving RCP emissions/concentrations scenario (see figure legend for details). Figures presenting similar information for the SREX regions contained in the other inhabited continents are presented in supplementary figures S-Box21-CMIP5-boxplots.

[INSERT BOX 21-3 FIGURE 2 HERE
Box 21-3 Figure 2 Caption: Regional average change in seasonal mean temperature and precipitation over five regions covering South and Central America for the period 2070-2100 relative to 1961-90 in GCM projections from the CMIP5 ensemble under four RCP scenarios (van Vuuren et al., 2011) compared with GCM projections from the CMIP3 ensemble under three SRES scenarios (IPCC, 2000). Regional averaged are based on SREX region definitions (see Figure 21-RegAmplFac). Temperature changes are given in ºC and precipitation changes in mm/day with axes scaled relative to the maximum changes projected across the range of models.]

Projected changes in daily temperature and precipitation are presented for two example indices, the 90th percentiles of the daily maximum temperature and daily precipitation amounts on wet days (a wet day is defined as a day when more than 1mm of rain falls and defining the statistic of interest for wet days only allows data from regions with only a few rainy days per year to be easily included in the calculations). Due to concerns over the number of events that need to be sampled to generate robust statistics on changes in extremes (Kendon et. al, 2008) changes in these indices were calculated over 30 year periods (1961-1990 for the baseline and two future periods, 2041-2070 and 2071-2100) and the analysis was focused on the less extreme daily events. For consistency with the example summary regional figure, Figure 1, projected changes were calculated for RCPs 4.5 and 8.5 and the results are displayed as a map for a given continental region and also regional averages over the SREX regions within that continent. Two examples are provided, for temperature changes over N America (Figure 3) and precipitation changes over Asia (Figure 4), and a full set can be found in supplementary figures S-Box21-CMIP5-dailychanges.

[INSERT BOX 21-3 FIGURE 3 HERE
Box 21-3 Figure 3 Caption: The frequency of 'hot days' (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961-1990) projected for the 2071-2100 period by the CMIP5 GCMs for North America. Top: Ensemble median frequency of 'hot days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'hot-day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of 'Hot days'of 10% is represented on the graphs by the dashed line.
[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]]

[INSERT BOX 21-3 FIGURE 4 HERE
Box 21-3 Figure 4 Caption: The frequency of 'very wet days' (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961-1990 with wet days defined as days with 1mm of precipitation or more) projected for the 2071-2100 period by the CMIP5 GCMs. Top: Ensemble median frequency of 'very wet days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'very wet day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of 'Very wet days' of 10% is represented on the graphs by the dashed line.
[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]]

_____ END BOX 21-3 HERE _____

Studies have also attempted to obtain regional information based on pattern scaling techniques in which regional temperature and precipitation changes are derived as a function of global temperature change. For example, in a recent paper Harris et al. (2012) used a Bayesian method complemented by pattern scaling and performance-based model weighting to calculate Probability Density Functions (PDFs) of temperature and precipitation change over sub-continental scale regions (Figure 21.4) under the A1B emission scenario based on an ensemble of simulations constrained to observations for the late 21st century. Although most impact studies might need local rather than sub-continental scale information, Figure 21.4 illustrates how the identification of the evolution of different percentiles of the distribution might be especially useful for risk assessment studies. Pattern scaling is indeed a valuable tool to estimate mean regional changes and associated uncertainty. It was for example used to calculate PDFs of temperature and precipitation change over different regions by Watterson (2008), Watterson and Whetton (2011), Watterson (2011), and Giorgi (2008).

[INSERT FIGURE 21-4 HERE
Figure 21-4: Evolution of the 5%, 17%, 33%, 50%, 66%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (upper panel) and annual precipitation (lower panel) for the Giorgi-Francisco (2000) regions and the globe with the A1B forcing scenario. Twenty year means relative to the 1961-1990 baseline are plotted in decadal steps using a common y-axis scale. The 5%, 50% and 95% percentile values for the period 2080-2099 are displayed for each region. (From Harris et al. 2012)]

21.3.3.1.3. Near-term decadal predictability

Compared to CMIP3, CMIP5 has an additional emphasis on near-term climate change, including intitialized experiments aimed at assessing decadal predictability. The uncertainty in near term projections is dominated by internal variability of the climate system, initial ocean conditions and inter-model response, rather than GHG forcing, and in fact the internal variability grows in importance at smaller spatial and temporal scales (Hawkins and Sutton 2009, 2010). Conversely, GHG forcing uncertainty becomes increasingly important on longer time scales, especially for surface air temperature (Hawkins and Sutton, 2009, 2010). Global warming for the period of 2016-2035 compared to 1986-2005 based on the CMIP5 multi model ensemble is *likely* of 0.4-1.0ºC, *more likely than not* closer to the lower end 0.4 C, and spatial patterns of near term warming are generally consistent with the AR4 (WGI Chapter 11). Differences across RCPs are small and about 50% of the warming is understood as the committed response to past emissions (WGI Chapter11). In terms of precipitation change patterns, it is more *likely than not that* in the next decade's precipitation will increase in regions of high precipitation and decrease in relatively dry regions (WGI Chapter 11).

The CMIP5 ensemble includes a new set of multidecadal near term prediction experiments (up to 2035) with initialized ocean state (WGI Chapter 11). Results from these experiments and analyses of un-initialized simulations show that there is a medium amount of evidence of the predictability of yearly to decadal averages of temperature both for the global average and for some geographical regions. Multi-model results for precipitation indicate a generally low level of predictability, except for some regions at higher northern latitudes and longer timescales. There is medium evidence that the Atlantic Multidecadal Variability (AMV) and Pacific Decadal Variability (PDV) patterns of climate variation exhibit predictability on timescales up to a decade (WGI Chapter 11). It is also shown that indices of global-mean temperature and Atlantic multi-decadal variability have statistically significant positive correlation with observations for most forecast periods (i.e., four-year averages ranging from 1–4 to 6–10 years) considered. At the regional scale, the retrospective prediction experiments for forecast periods of 1 to 10 years have statistically significant correlations with the observations (greater than 0.6, significant at the 95% confidence level) over much of the globe for temperature and over several regions for precipitation. [Section 11.2.2]. The correlation is improved by the ocean initialization over the North Atlantic, regions of the South Pacific and small continental areas of the Northern Hemisphere for temperature, while the effect of initialization for precipitation is negligible.

21.3.3.1.4. Changes in hydroclimate and extreme events

Changes in the characteristics of surface hydroclimatology, and especially extremes, are fundamental for an assessment of related impacts. Based on an analysis of observations, global and regional climate model simulations, Giorgi et al. (2011) defined an index of hydroclimatic intensity (HY-INT) incorporating a combined measure of precipitation intensity and mean dry spell length. They found that a ubiquitous global and regional increase in HY-INT was a strong hydroclimatic signature in model projections consistent with observations for the late decades of the 20th century, suggesting that HY-INT may be an important hydroclimatic indicator of global warming for use in detection/attribution and impact studies. The increase in intensity of precipitation (and thus risk of flood) and summer drought occurrence over mid-continental land areas is a robust signature of global warming, both in observations for recent decades and in model projections (Trenberth 2011).

CMIP5 projections of temperature extremes essentially confirm results from the CMIP3, namely a decrease in the frequency of cold days and nights, an increase in the frequency of warm days and nights, an increase in the duration of heat waves and an increase in the frequency and intensity of high precipitation events, both in the near term and

far future (SREX Report, WGI Chapter 12). Some relevant summary statistics on CMIP5 projections of changes in daily temperature and precipitation extremes over the main continents and the SREX regions (Figure 21.1) are introduced in Box 21-3 and accompanying supplementary material.

Concerning tropical cyclones, there is still little confidence in past trends and near term projections of tropical cyclone frequency and intensity (Senevirante et al 2012; SREX Report). The global tropical cyclone frequency is projected to either not change or decrease and show different responses at the basin scale (Knutson et al. 2010). Concurrently, a *likely* overall increase in maximum wind speed and precipitation is expected, but region-specific conclusions are still uncertain (Knutson et al. 2010).

Regional circulations, such as the monsoon, are expected to change. Seth et al. (2011) and Sobel and Camargo (2011) found in the CMIP3 ensemble of 21st century projections a redistribution of precipitation from spring (early monsoon phase) to summer, mature phase in both northern (North America, West Africa and Southeast Asia) and southern (South America, Southern Africa) hemisphere monsoon regions. More generally, model projections indicate a prevailing decrease of the intensity of monsoon circulation, but an increase of monsoon rain due to the greater water-holding capacity of the atmosphere along with later monsoon onset leading to longer monsoon seasons (WGI Chapter 14).

21.3.3.1.5. Major modes of variability

ENSO is the mode of variability that has received most attention from a climate impacts point of view with significant effects on human and natural systems (http://iri.columbia.edu/climate/ENSO/societal/index.html). Seasonal forecasting of El Niño behavior has significant skill (AR4-WG1 Chapter 8) and is used to providing advanced warnings of its impacts worldwide. Recent research has underscored the complexity of the ENSO system and provided some explanation for this, such as the non-symmetric amplitude between El Nino and La Nina (An, 2005, WGI Chapter 14). While we do not have definitve answers regarding the effect of anthropogenic forcing on ENSO, we know that it experiences decadal and longer term modulations that occur with relatively small changes in the mean climate state of the tropical Pacific. Model improvements in the reproduction of ENSO are evident in some of the models used for the CMIP5 simulations. For example CCSM4 shows good performance in reproducing the asymmetry between El Nino and La Nina durations (Deser et al., 2011). Although model projections indicate that ENSO remains a major mode of tropical variability, there is little evidence to indicate changes forced by GHG warming which are outside the natural modulation of ENSO occurrences.

The North Atlantic Oscillation (NAO) is a major model of variability for the northern Hemisphere mid-latitude climate. Model projections indicate that the NAO phase is *likely* to become slightly more positive (WGI Chapter 14) due to GHG forcing, but the NAO will be dominated by its large natural fluctuations. Model projections indicate that the Southern Annular Mode (SAM), a major model of variability for the southern hemisphere, is *likely* going to weaken as ozone concentrations recover through the mid-21st century (WGI Chapter 14).

21.3.3.1.6. Results from dynamical and statistical downscaling experiments

Dynamical and statistical downscaling techniques have been increasingly applied to regional climate change simulations, often as part of multi-model intercomparison projects. In this regard a new international program has been implemented, the COordinated Regional Downscaling Experiment (CORDEX, Giorgi et al. 2009), that will provide a framework for the assessment of dynamical and statistical downscaling techniques and the production of a new generation of climate projections over regions worldwide for use in impact and adaptation work. A few papers have already become available describing the first CORDEX experiments over different domains, and it is expected that CORDEX will in fact become a reference framework for downscaling experiments in the same way that CMIP5 is for global model experiments.

A large number of RCM-based climate projections for the European region were produced as part of the European projects PRUDENCE (Christensen et al. 2007; Deque et al. 2007) and ENSEMBLES (Hewitt 2005; Deque and

Somot 2010) where multiple RCMs have been run as driven by different GCMs for various scenarios . They all provide a generally consistent picture of seasonally and latitudinally varying patterns of change, which Giorgi and Coppola (2007) summarized with the term "European Climate Change Oscillation (ECO)", consisting of a dipole pattern of precipitation change, with decreased precipitation to the south (Mediterranean) and increased to the north (Northern Europe) following a latitudinal/seasonal oscillation centered over the Mediterranean in winter and moving northward to central Europe in summer. As a result, the Mediterranean region is projected to be much drier and hotter than today in the warm seasons (Giorgi and Lionello 2008), and central/northern Europe much warmer and wetter in the cold seasons (Kjellstrom and Ruosteenoja, 2007). An increase of interannual variability of precipitation and summer temperature is also projected throughout Europe, with a decrease in winter temperature variability over Northern Europe (Schar et al. 2004; Giorgi and Coppola 2007; Lenderink et al. 2007). The broad patterns of change in regional model simulations generally follow those of the driving global models (Christensen and Christensen 2007; Deque et al. 2007), however fine scale differences related to local topographical, land use and coastline features are produced. For example, east-west winter precipitation change dipoles are projected across the Appenine chain as a result of the effect of this mountain system (Gao et al. 2006; Coppola and Giorgi 2010). These RCM simulations also projected an increase in a broad range of climate extremes (Beniston et al. 2007), such as heat waves, maximum drought length and number of hot days, especially over Central and Southeastern Europe and the Mediterranean (Gao et al. 2006; Beniston et al. 2007; Kjellstrom et al., 2007; Diffenbaugh et al., 2007), precipitation intensity and extremes especially over Central, Western and Northern Europe (Frei et al. 2006; Beniston et al. 2007, Buonuomo et al. 2007; Fowler et al. 2007; May 2008; Fowler and Ekstrom 2009; Kysely and Beranova, 2009; Kendon et al. 2010; Hanel and Buishand 2011; Kysely et al. 2011). Studies have also consistently shown that the distribution of seasonal temperature anomalies in the future is expected to be broader than today, particularly over central and southern Europe. This will lead, along with a shift of the distribution, to a higher frequency and intensity of extreme hot and dry summers (e.g. Schar et al. 2004; Seneviratne et al. 2006; Beniston et al. 2007; Coppola and Giorgi 2010), for which a substantial contribution is given by land-atmosphere feedbacks (Seneviratne et al. 2006; Fischer et al. 2007; Seneviratne et al. 2010; Hirschi et al. 2011; Jaeger and Seneviratne 2011). In general, the Mediterranean region is consistently projected to be much more arid than today (Rowell and Jones 2006; De Castro et al. 2007; Giorgi and Lionello, 2008; Gao and Giorgi 2008; Onol and Semazzi 2009; Trnka et al. 2011), and coupled atmosphere-ocean RCM simulations indicate that ocean feedbacks can significantly amplify the regional climate change signal over different regions of Europe (Somot et al. 2008). Concerning storminess projections , some studies based on ensembles of RCM simulations indicate a prevailing increase in winter mean daily and peak wind speed over Northern Europe (Rockel and Woth 2007; Albrecht et al. 2010, Bengtsson et al. 2009, Ulbrich et al. 2009), while more mixed results are found over the Mediterranean (Lionello et al. 2008; Giorgi and Lionello 2008). Recently, the first set of high resolution (dx = 12.5 km) projections over the EURO-CORDEX domain have been completed (Jacob et al. 2013). Both for the RCP8.5 and RCP4.5 scenarios the temperature and precipitation change patterns are generally consistent with those found for the ENSEMBLES project, further strengthening the robustness of those results.

As part of the ENSEMBLES and AMMA projects, 9 RCMs were run for the period 1990-2050 (A1B scenario) over domains encompassing the West Africa region with lateral boundary conditions from different GCMs. The RCM-simulated West Africa monsoon showed a wide range of response in the projections, even when the models were driven by the same GCMs (Paeth et al. 2011) (Figure 21.5). Although at least some of the response patterns may be within the natural variability, this result along with the fact that the model biases were not strongly tied to the driving GCMs suggests that for Africa, and probably more generally the tropical regions, local processes and how they are represented in models play a key factor in determining the precipitation change signal. Similar conclusions were found for an all-Africa RCM simulation of 1980-2100 (A1B scenario) by Mariotti et al. (2011) as well as a climate change projection over South Africa with a variable resolution model (Engelbrecht et al. 2009). Diallo et al. (2012) showed that ensemble averaging of RCM simulations tends to compensate systematic errors from the individual models and provide more consistent results. They found a prevailing decrease in peak monsoon rainfall over the western Sahel for the early decades of the 21st century in an ensemble of 4 RCM simulations driven by different GCMs. These results indicate that uncertainties in projections of the hydrologic cycle of Africa remain high and need large ensembles of model simulations in order to be fully characterized.

Statistical downscaling techniques have also been applied to the Africa region (Hewitson and Crane 2006; McKellar et al. 2007; Lumsden et al. 2009; Steynor et al. 2009). In general, methodological developments since the AR4 have

been limited (see, for example reviews in Paeth et al., 2011, and Brown et al., 2008) and activities have focused more on the applications (e.g. Mukheibir, 2007, Nawaz et al, 2007, Gerbaux et al, 2009) for regional specific activities in the context of IAV work. Some promising developments relate to combining dynamical and statistical approaches, as for example in Paeth and Diederich (2010), who use an extended weather generator to optimize inputs to a hydrological model for application in west Africa. New work is also emerging that is not specific to Africa, but inclusive of all terrestrial regions. For example, Benestad (2011) developed a global downscaled product for station locations across all continents based on CMIP3, and draws a range of conclusions for regions including Africa, although the robustness of the statistical downscaling relationship for a number of locations is weak. Other activities are underway for similar globally extensive downscaling based on new CMIP5 GCMs with the purpose of producing gridded products (Ref to be eventually added here). However, the majority of statistical downscaling has been related to application of existing data products and is mostly not reported in the peer reviewed scientific literature, being found instead in the grey literature of project and institutional reports.

[INSERT FIGURE 21-5 HERE
Figure 21-5: Linear changes (i.e. changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001-2050 period from 10 individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land cover changes (see Paeth et al. 2011 for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 5% level are marked by black dots. (From Paeth et al. 2011)]

Several RCM experiments have been conducted for the South America continent, also as part of the CLARIS project (Menendez et al. 2010; Nunez et al. 2009; Sorensson et al. 2010; Marengo et al. 2009, 2010), and time-slice high resolution GCMs have been analyzed over the continent (Kitoh et al. 2011). In addition, pattern scaling was used to produce climate change scenarios over Southern South America (Cabre et al. 2010). Overall these studies revealed varied patterns of temperature and precipitation change, depending on the global and regional models used, however a consistent change found in many of these studies was an increase in both precipitation intensity and extremes, especially in areas where mean precipitation was projected to also increase.

The Central American region has emerged as a prominent climate change hot-spot since the AR4, especially in terms of a consistent decrease of precipitation projected by most models. Regional model studies focusing specifically on Central America projections are however still sparse. For example Campbell et al. (2010) performed a downscaling study on two GCMs finding some robust precipitation changes, such as a general drying in June-October, which is consistent with the more general analysis of CMIP3 results by Rauscher et al. (2008) and Rauscher et al. (2011) who however found that most of the precipitation reduction there occurred in June-July, just before the August mid-summer drought.

For both the South America and Central America regions, a first ensemble of RCM CORDEX projections were produced by Coppola et al. (2012), Fuentes-Franco et al. (2013) using different driving global models, different regional model configurations and the RCP8.5 and RCP4.5 scenarios. Preliminary analysis of the results showed that the change signals, especially for precipitation, were sensitive not only to the driving GCM fields, but also to the internal model physics, and in particular to the representation of land surface processes and feedbacks and the response of convection to SST forcing. This adds an element of uncertainty to the interpretation of fine scale change patterns that needs to be assessed with the use of large RCM ensemble. Diro et al. (2013) also showed that the simulation of tropical storms in the Atlantic and Pacific are sensitive to the convection scheme used. When using the better performing schemes, they found that the frequency of tropical cyclones decreased in the tropical Atlantic and eastern Pacific coastal areas while it increased over the central Pacific and northern Atlantic, with these changes being mostly driven by the changes in SST and wind shear. The experiments also shown a consistent increase in the frequency of intense and long lasting tropical storms.

Since the AR4 there has been considerable attention given to producing higher resolution future projections of climate change over North America through the application of RCMs and higher resolution global time slices. The North American Regional Climate Change Assessment Program (NARCCAP) has been a major multi-institutional effort using a number of different RCMs (with a resolution of 50 km) driven by different global climate

models (GCMs) from the CMIP3 dataset, over the domain of most of North America (Mearns et al., 2009; 2012). Results indicate considerable variations in future climate based on the different RCMs, even when driven by the same GCM (Figure 21.6). In winter there tends to be more agreement across the GCMs and the RCMs for change in precipitation compared to in the summer, when the RCMs tend to depart more distinctly from the future projections of the GCMs (Mearns et al., 2013; De Elia and Cote 2010). This may indicate a lack of robustness in the projected precipitation changes in summer, but in-depth process level analysis will be necessary to determine this. There is also a tendency for the uncertainty across the driving GCMs to dominate for winter temperature and precipitation, but the uncertainty across the different RCMs dominates in the summer season. More detailed investigations of subregions of the NARCCAP domain have also been performed (e.g. Solowski and Pvelski 2012; Rawlins et al. 2012) Bukovsky et al. (2013) investigated the behavior of the NARCCAP models with regard to the North American Monsoon and was able to separate out the effects of the driving GCMs and the RCMs regarding error propagation. The GCM-RCM combinations that better produced the monsoon characteristics tended to indicate decreases in monsoon rainfall.

[INSERT FIGURE 21-6 HERE
Figure 21-6: Change in summer (JJA) average temperature (2041-2070 minus 1971-2000) from (top left) the NCAR CCSM3, (top right) the MM5 regional climate model driven by the CCSM3; (bottom left) the WRF model, driven by CCSM3, and (bottom right) the Canadian CRCM, driven by CCSM3. Temperature is in °C. Data from the NARCCAP program. (From Mearns et al., 2009, 2013)]

Other regional modeling efforts for sub-regions of North America include those of Hostetler (in preparation), Caya and Biner (2011) Subin et al. (2011), Salathé et al., (2008, 2010), Dominguez et al. (2010), De Elia et al. (submitted), Lofgren et al. (in preparation). In the realm of statistical downscaling and spatial disaggregation, considerable efforts have been devoted to applying techniques for the entire US and parts of Canada (e.g., Maurer et al., 2007; Hayhoe et al., 2010). These methods are particularly useful for driving impacts models, since they are produced at very high resolutions (e.g., 10 km), but usually only include temperature and precipitation. Comparisons among the spatial disaggregation techniques and dynamical downscaling are underway including the differential effects on impacts and adaptation planning (e.g., Barsugli et al., in progress).

Numerous high resolution RCM projections have been carried out over the East Asia continent, and some of these tend to produce results that are actually not in line with those from GCMs. For example, Ashfaq et al. (2009) used an RCM with 25 km grid spacing to find that enhanced greenhouse forcing resulted in a predominant suppression of South Asia summer monsoon precipitation, a delay in monsoon onset and a an increase in monsoon break periods, while most GCMs tend to produce increased South Asia monsoon precipitation (WGI Chapter 14). These were mostly attributed to a weakening of the monsoon flow and a suppression of the dominant intraseasonal oscillatory modes. As another example, Gao et al. (2011) completed a climate projection at 20 km grid spacing over East Asia and found that while the forcing GCM produced a prevailing increase in summer monsoon precipitation, in agreement with most GCM-based projections, the nested RCM showed large areas of decreased summer precipitation amounts in response to the high resolution topographical forcing of the Tibetan Plateau and other topographical complexes. Similarly a series of double nested RCM scenario simulations were performed for the Korea peninsula reaching a grid spacing of 20 km (Im et al. 2007a; 2008a,b; 2010; 2011a,b). They indicated a complex fine scale structure of the climate change signal, particularly for precipitation, also forced by local topographical features and a consistent increase in intense and extreme precipitation events. While it is difficult to clearly establish whether the RCM simulations are more credible, which would require large ensembles, all these high resolution RCM experiments do point out the importance of regional and local topographical forcings in modulating the response of regional circulations, e.g. the monsoon, and of local phenomena, e.g. tropical convection.

Both RCM and variable resolution model experiments have been conducted over the Australian continent or some of its sub-regions (Watterson et al. 2008; Nunez and Mc Gregor 2007; Song et al. 2008), showing that a local fine scale modulation of the large scale climate signal occurs in response to topographical and coastal forcings. Statistical downscaling has been applied for a number of focused studies over Australia. Timbal et al (2008) evaluate the consistency between statistical downscaling and projections from the GCMs using two different statistical downscaling methods. They find that along with the higher resolution of the downscaling, the downscaled and direct

model projections are largely consistent across the 15 GCMs used, and averaged across the southwest of Western Australia, indicate a general decline of precipitation. More recently Yin et al (2010) focus on new methodological developments in downscaling, using an adapted Self Organizing Map procedure based on Hewitson and Crane (2006), and in common with other statistical downscaling studies finds the most notable challenge is downscaling precipitation in arid zones.

21.3.3.2. Oceans and Sea Level

Contributions to global sea level rise include thermal expansion, glacier and ice cap melting, Greenland ice sheet and Antarctic iceberg calving and ice sheet melting. Regional sea level change can be quite different from global sea level change due to changes in circulations and associated wind stress, changes to the geoid and crustal subsidence and rebound (WGI Chapter 3).

From paleo records there is evidence that during the last 3 million years global mean sea level (GMSL) was more than 6 m higher than present, with global mean temperatures being 2-3 C warmer than present. The rate of GMSL rise has increased in the last 200 years, to about 1.7 +/- 0.2 mm/year during the 20th century and 2.8-3.6 mm/year since 1993 (WGI Chapter 3). Since 1970 the greatest contributions to GMSL (combined 80%) rise have been from ocean warming/expansion and glacier melting, however the rate of the contributions from Greenland and Antarctica ice has been increasing since the 1990s. An important advance compared to the AR4 is the closure of the observations budget for recent decades due to an improved set of observations, in particular the GRACE satellite data. In addition, estimates of 20th century GMSL increase from AOGCM simulations are now much closer to observations due to better understanding and modeling of relevant processes (WGI Chapter 11). The mean regional pattern of sea surface salinity has been enhanced, with saline surface waters in the evaporation-dominated mid-latitudes becoming more saline, and relatively fresh surface waters in rainfall-dominated tropical and polar regions becoming fresher.

Evidence is strong that the biogeochemical state of the ocean has changed (WGI Chapter 3). The ocean inventory of anthropogenic carbon dioxide has increased, from 114 ± 22 PgC in 1994 to 151 ± 26 PgC in 2010 and this is in broad agreement with the expected change resulting from the increase in atmospheric CO2 concentrations and change in atmospheric O2/N2 ratios (WGI Chapter 3). The uptake of CO2 by the ocean has resulted in a gradual acidification of seawater, with observations showing declines in pH in the mixed layer between -0.0015 and -0.0024 yr^{-1}.

Concerning GMSL projections (WGI Chapter 13), under all the RCP scenarios, the time-mean rate of GMSL rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010, with ocean thermal expansion and glacier melting *likely* to make the largest contributions to this rise. For the period 2081 to 2100 compared to 1986 to 2005, GMSL rise is *likely* to lie in the range 0.29–0.55 m for RCP2.6, 0.36–0.63 m for RCP4.5, 0.37-0.64 for RCP6.0, and 0.48–0.82 m for RCP8.5. The upper end of this range is higher than in the AR4, but the confidence in these estimates is still limited due to limited understanding of some key processes, such as rapid changes in ice sheet dynamics and the differences between estimates with semi-empirical and process-based models, with the former giving higher upper estimates (higher than 1.0 m).

Projections of regional sea level changes, both based on the CMIP3 and CMIP5 models, indicate a large regional variability of sea level rise (even more than 100% of the GMSL rise), with areas undergoing much larger or smaller rise than the global average in response to different regional processes (WGI Chapter 13). However, by the end of the 21st century it's *very likely* that over about 95% of the oceans will undergo sea level rise, with the remaining 5% experiencing a decline mostly in high latitude regions and 75-80% of coastlines experiencing a sea level rise within 20% of the GLSL one.

Regional sea level changes for the next decades will largely be dominated by internal dynamical variability of the climate system, while on longer time scales changes in regional sea level will likely be dominated by changes in ocean dynamics. Some preliminary analysis of the CMIP5 ensembles, for example, indicates area of maximum

steric sea level rise in the Northern Atlantic, the northwestern Pacific off the East Asia coasts, the eastern coastal oceanic regions of the Bay of Bengal and the western coastal regions of the Arabian Sea (WGI Chapter 13).

Some analysis of the past decades indicate that the increase in storm surges and extreme sea level events is generally in line with the increase in mean sea level (Menendez and Woodworth 2010; Lowe et al. 2010; Woodworth et al. 2011). Dominant modes of variability, such as ENSO and the NAO, are also found to significantly affect extreme sea levels in a number of regions (Lowe et al. 2010). Some low lying areas, such as Venice (Carbognin et al. 2010) and the deltaic regions of the Bay of Bengal (Unnikrishnan and Shankar 2007), show trends in sea level much higher that the global average, also because eof subsidence in some cases (e.g. Venice). Positive wave height trends are found in many areas of the North Atlantic, North pacific, U.S. coasts and Southern ocean, with modulation associated with main modes of climate variability. Projections of storm surges in European coasts have used RCM-produced wind fields to force storm surge models, and prevailing increases in extreme storm surges were found (Debernard and Roed 2008; Wang et al. 2008). However changes in storm surges are tied to changes in atmospheric circulations, and may be highly regionally dependent. Increase of GMSL is likely to affect storm surges and increase the frequency of extreme sea level events.

Projections of changes in the Atlantic Meridional Overturning Circulation (AMOC) from the CMIP5 models indicate that it is *very likely* that the AMOC will weaken in the 21st century as a result of increased GHG concentrations (by 20-30% in the RCP4.5 scenario and 36-44% in the RCP8.5) but it is *very unlikely* that it will undergo an abrupt transition or collapse for the scenarios considered (WGI Chapter 12).

21.3.3.3. Air Quality

Changes in air pollutants such as near surface ozone and particulate material may have effects on human health, agriculture and natural ecosystems. These changes may depend on changes in emissions or changes in climatic and meteorological conditions affecting transport and removal of the pollutants. Therefore the issues of climate change and air quality are deeply interconnected (Giorgi et al. Meleux 2007).

Since the AR4 the interest in climate-air quality interactions has increased and more studies have become available addressing the issue of the effects of both climate and emission changes on air quality. Most of these studies focused on the continental United States and Europe, and utilized both global and regional climate and air quality models run in off-line or coupled mode. Regional modeling studies over the United States or some of its sub-regions include, for example, those of Hogrefe et al. (2004), Knowlton et al. (2004), Steiner et al. (2006), Dawson et al. (2006), Lin et al. (2008), Weaver et al. (2009), Zhang et al. (2008), while examples of global modeling studies include Murazaki and Hess (2006), Stevenson et al. (2006), Shindell et al. (2006), Doherty et al. (2006). Weaver et al. (2009) provide a synthesis of simulated effects of climate change on ozone concentrations in the U.S. using an ensemble of regional and global climate and air quality models. These studies indicate a predominant increase in near-surface ozone concentrations, particularly in the Eastern U.S. (Figure 21.7) mostly tied to higher temperatures and corresponding biogenic emissions. An even greater increase was found in the frequency and intensity of extreme ozone concentration events, which are the most dangerous for human health.

Examples of regional studies of air quality changes in response to climate change over Europe include Langner et al. (2005), Forkel and Knocke (2006) , Szopa and Hauglustaine (2007), and Meleux et al. (2007), Carvalho et al. (2010), Engartd et al. (2009), Andersson and Engardt (2010), Kruger et al. (2008), Athanassiadou et al. (2010). All these studies indicated the potential of large increases in near surface summer ozone concentrations especially in Central and Southern Europe due to much warmer and drier projected summer seasons (Figure 21-8).

[INSERT FIGURE 21-7 HERE
Figure 21-7: Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2081-2100 minus 1981-2000) MDA8 summer ozone concentrations across (left-hand panels) all 7 experiments (5 regional and 2 global) and, for comparison purposes (right-hand panels) not including the WSU experiment (which simulated July only conditions). (From Weaver et al. 2009)]

[INSERT FIGURE 21-8 HERE
Figure 21-8: Difference in average summer daily ozone mean (left panel) and peak (right panel) concentration over Europe due to climate change, (2071-2100 minus 1961-1990), A2 scenario. (From Meleux et al. 2007)]

In general, while a consistently predominant increase of ozone concentrations due to climate change was found in these experiments, results were more mixed and regionally/seasonally dependent for other pollutants such as PM, sulfur and nitrogen compounds. It should be mentioned that most studied addressed the issue of climate effects on ozone without changes in anthropogenic emission. However, these are likely to change as well, and thus modulate the climate-related signals.

21.3.3.4. Cryosphere

The cryosphere is one of the most sensitive components of the climate system to global warming, and this response, which has profound implications for changes in sea level rise and atmospheric circulations, is determined by very complex processes, some of which are still poorly understood (e.g. ice flow dynamics).

New and improved data have become available since the AR4 to evaluate changes in the cryosphere (WGI Chapter 4), most notably the GRACE satellite ones, which have allowed more accurate assessments of the ice sheet mass balance. These improved observations show that the retreat of Arctic ice in all seasons has continued, at a rate of 3.9% per decade annually and 12.2% per decade during the summer during the period 1979-2011. The thickness, concentration and volume of arctic ice have also decreased, with a decrease in mean winter thickness by 48% between 1980 and 2009. Conversely, the total extent of Antarctic ice has increased slightly (1.4% per decade) between 1979 and 2011, with strong regional differences.

Retreat of mountain glaciers is widespread, with varying rates across regions, and uncertainty about the global rate. In particular, increasing loss of glacier mass has been observed in recent decades over Central Europe, Alaska, the Canadian Arctic and the Southern Andes. Several hundred glaciers globally have completely disappeared in the last 30 years.

Because of better techniques and more data, confidence has increased in the measurements of Greenland and Antarctica ice sheets. These indicate that parts of the Antarctic and Greenland ice sheets have been losing mass over the last two decades and contribute to global sea level rise. During 1993-2012, Greenland lost on average 123 ± 22 Gt yr-1 (0.34 mm/year of SLE) and Antarctica lost 65 ± 33 Gt yr-1 (0.18 mm/year of SLE). In the GRACE period 2005–2010, the losses were higher, 228 ± 54 Gt yr-1 in Greenland and 112 ± 58 Gt yr-1 in Antarctica. These were mostly caused by changes in ice flow in Antarctica, and a mix of changes in ice flow and increases in snow/ice melt in Greenland. Ice shelves in the Antarctic peninsula are also continuing a long-term trend of retreat and partial collapse started some decades ago. In total global SLR due to the contributions of Greenland and Antarctic ice sheets was 1.2+/- 0.2 mm/year for 1993-2010 and 1.7 +/1 0.5 mm/year for 2005-2010 (WGI Chapter 4).

New data, both in situ and from satellite confirm a decrease in snow cover extent in most months, particularly in spring (8% in 1970-2010 compared to 1922-1970), with marked regional and seasonal variations and with a decline in the duration of northern hemisphere snow season of about 5.3 days per decade (WGI Chapter 4). During the past three decades, significant permafrost degradation occurred. Permafrost temperature has increased (up to 3°C since the late-1970s in some regions of the Arctic) and the areal extent of permafrost is declining. The thickness of seasonally frozen ground has decreased in the 20th century across the Russian European North and from 1960 to the present on the Qinghai-Xizang (Tibetan) Plateau. The thaw season has expanded by more than two weeks from 1988 through 2007 across central and eastern Asia.

Twenty first century projections of cryosphere changes based on the CMIP5 ensemble show long-term reductions in Northern Hemisphere sea ice areal coverage in both hemispheres, from 39% for RCP2.6 to 94% for RCP8.5 in September and from 9% to 35% in February by the end of the century (WGI Chapter 12). The models indicate a nearly ice-free Arctic at the end of summer for warming greater than 2C. The CMIP5 models also better capture the rapid decline in summer Arctic sea ice observed during the last decades than CMIP3 models. Future projections of

Southern Hemisphere sea ice remain comparatively more uncertain, with the CMIP5 multi-model ensemble projecting, for the end of the 21st century, a decrease in Southern Hemisphere sea ice extent from 14% for RCP2.6 to 57% for RCP8.5 in February and from 9% to 29% in September, and a large inter-model scatter. The models show no evidence of critical thresholds in the transition from perennial ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible. Projections of decrease in Northern Hemisphere spring snow covered area in the CMIP5 models are fairly coherent (decrease of about 7% in RCP2.6 and 25% RCP8.5 by 2100). Surface permafrost area is projected to decrease between 37% (RCP2.6) to 81% (RCP8.5) by 2100.

21.4. Cross-Regional Phenomena

Thus far, this chapter has covered climate change-related issues that have a regional expression in one part of the world or another. In principle, these issues can be studied and described, *in situ*, in the regions in which they occur. However, there is a separate class of issues that transcends regional boundaries and demands a different treatment. In order to understand such cross-regional phenomena, knowledge is required of critical but geographically remote associations and of dynamic cross-boundary flows. The following sections consider some examples of these phenomena, focusing on trade and financial flows and migration. Though these issues are treated in more detail in Part A of this report, they are restated here in Part B to stress the importance of a global perspective in appreciating climate change challenges and potential solutions at the regional scale.

21.4.1. Trade and Financial Flows

Global trade and international financial transactions are the motors of modern global economic activity, and are inextricably linked to climate change through a number of interrelated pathways: (i) as a direct or indirect cause of anthropogenic emissions, (ii) as a predisposing factor for regional vulnerability to the impacts of climate change, (iii) through their sensitivity to climate trends and extreme climate events, and (iv) as an instrument for implementing mitigation and adaptation policies.

21.4.1.1. International Trade and Emissions

The contemporary world is highly dependent on trading relationships between countries in the import and export of raw materials, food and fibre commodities and manufactured goods. A rapidly growing world population and expanded economic activity in many developing countries during the past two decades has fuelled increasing demand for imports. The engines of manufacturing are now located in developing countries with a young and relatively cheap workforce, with only high value products retaining competitiveness in the developed world. Even during a period of general recession since 2008, economic development in many emerging, export-led economies (e.g. China, India, Ghana and Brazil) succeeded in bucking the global trend (World Bank, 2012).

Bulk transport of these products, whether by air, sea or over land, is now a non-trivial contributor to emissions of greenhouse gases and aerosols. Furthermore, the relocation of manufacturing has transferred net emissions via international trade from developed to developing countries (see Figure 21-9), and most developed countries have increased their consumption-based emissions faster than their domestic (territorial) emissions (Peters *et al.*, 2011). This regional transfer of emissions is commonly referred to in climate policy negotiations as "carbon leakage" (Barker *et al.*, 2007), though only a very small portion of this can be attributed to climate policy ("strong carbon leakage"), a substantial majority being due to the effect of nonclimate policies on international trade ("weak carbon leakage" – Peters, 2010). A particular example of strong carbon leakage concerns the conversion of land use from the production of food to bioenergy crops. These crops sequester carbon otherwise extracted from the ground as fossil fuels, but in the process displace demand for food production to land in other regions, often inducing land clearance and hence an increase in emissions (Searchinger *et al.*, 2008), though the empirical basis for this latter assertion is disputed (see Kline and Dale, 2008).

[INSERT FIGURE 21-9 HERE
Figure 21-9: Growth rates from 1990-2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macrovariables, all indexed to 1990 (Peters et al., 2011).]

21.4.1.2. Trade and Financial Flows as Factors Influencing Vulnerability

The increasingly international nature of trade and financial flows (commonly referred to as globalisation), while offering potential benefits for economic development and competitiveness in developing countries, also presents high exposure to climate-related risks for some of the populations already most vulnerable to climate change. Examples of these risks, explored further in Chapters 7-9, 12 and 13 of Part A, include:

- Severe impacts of food price spikes in many developing countries (including food riots and increased incidence of child malnutrition) such as occurred in 2008 following shortfalls in staple cereals, due to a coincidence of regional weather extremes (e.g. drought) in producer countries, the reallocation of food crops by some major exporters for use as biofuels (an outcome of climate policy – see previous section) and market speculation (Ziervogel and Ericksen, 2010). Prices subsequently fell back as the world economy went into recession, but spiked again in early 2011for many of the same reasons (Trostle *et al.*, 2011), with some commentators predicting a period of rising and volatile prices due to increasing demand and competition from biofuels (Godfray *et al.*, 2010).
- A growing dependence of the rural poor on supplementary income from seasonal urban employment by family members and/or on international financial remittances from migrant workers (Davies *et al.*, 2009). These workers are commonly the first to lose their jobs in times of economic recession, which automatically decreases the resilience of recipient communities in the event of adverse climate conditions.On the other hand, schemes to provide more effective communication with the diaspora in times of severe weather and other extreme events can provide rapid access to resources to aid recovery and reduce vulnerability (Downing, 2012).
- Some aspects of international disaster relief, especially the provision of emergency food aid over protracted periods, has been cited as an impediment to enhancing adaptive capacity to cope with climate-related hazards in many developing countries (Schipper and Pelling, 2006). Here, international intervention, while well-intentioned to relieve short-term stress, may actually be counter-productive in regard to the building of long-term resilience.

21.4.1.3. Sensitivity of International Trade to Climate

Climate trends and extreme climate events can have significant implications for regional resource exploitation and international trade flows. The clearest example of a major prospective impact of climate change concerns the opening of Arctic shipping routes as well as exploitation of mineral resources in the exclusive economic zones (EEZs) of Canada, Greenland/Denmark, Norway, Russia and the USA (Figure 21-10a, and see Chapter 28). For instance, the CCSM4 climate and sea ice model has been used to provide projections under RCP4.5, RCP6.0 and RCP8.5 forcing (see Box 21-1) of future accessibility for shipping to the sea ice hazard zone of the Arctic marine environment defined by the International Maritime Organization (Stephenson *et al.*, 2013 – Figure 25-10a). Results suggest that moderately ice-strengthened ships (Polar Class 6), which are estimated under baseline (1980-1999) conditions to be able to access annually about 36 % of the IMO zone, would increase this access to 45-48 % by 2011-2030, 58-69% by 2046-2065 and 68-93% by 2080-2099, with almost complete accessibility projected for summer (90-98% in July-October) by the end of the century (Stephenson *et al.*, 2013). Estimates are also presented for three major cross Arctic routes: the Northwest Passage, Northern Sea Route (which is part of the Northeast Passage), and Trans-Polar Route (Figure 21-10a). This could represent significant distance savings for trans-continental shipping currently using routes via the Panama and Suez Canals (Stephenson *et al.*, 2011). Indeed, in 2009 two ice-hardened cargo vessels – the Beluga Fraternity and Beluga Foresight – became the first to successfully traverse the Northeast Passage from South Korea to the Netherlands, a reduction of 5,500 km and 10 days compared to their traditional 20,000 km route via the Suez Canal, translating into an estimated saving of some $300,000 per ship, including the cost of standby icebreaker assistance (Smith, 2009; Det Norsk Veritas, Beluga). A projection

using an earlier version of the sea ice model under the SRES A1B scenario, but offering similar results (with forcing comparable to RCP 6.0), is presented in Figure 21-11b, which also portrays winter transportation routes on frozen ground. These routes are heavily relied upon for supplying remote communities and for activities such as forestry and, in contrast to the shipping routes, are projected to decline in many regions (Figure 21-10b).

[INSERT FIGURE 21-10 HERE
Figure 21-10: (a) Marine exclusive environmental zones (EEZs – dashed lines) of Canada, Greenland/Denmark, Norway, Russia, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the IMO Guidelines Boundary for Arctic shipping (thick black border). After Stephenson (2013). (b) Projected change in accessibility of maritime and land-based transportation by mid-century (2045-2059 relative to 2000-2014) using the Arctic Transport Accessibility Model and CCSM3 climate and sea ice estimates assuming an SRES A1B scenario. Green areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).]

A second illustration of how the risk of adverse climate changes may have contributed to anticipatory adaptive actions affecting countries in other regions of the world and potentially influencing commodity markets, relates to the purchase or renting of large tracts of productive land in parts of Africa, Latin America, Central Asia and Southeast Asia by countries in Europe, Africa, the Gulf and South and East Asia (De Schutter, 2009; Cotula *et al.*, 2011; Zoomers, 2011). While there is clearly a profit motive in many of these purchases (i.e., cheap and fertile land and the opportunity to cultivate high value food or biofuel crops), there is also a concern that domestic agricultural production in some countries will be unable to keep pace with rapid growth in domestic demand and changing dietary preferences, especially in agricultural regions affected by frequent shortfalls due to droughts, floods and cyclones (Cotula *et al.*, 2011), or threatened by sea-level rise (Zoomers, 2011). Land acquisition on such a large scale raises a number of ethical issues relating to local access to food and the appropriate and sustainable management of the land (Deininger and Byerlee, 2012). These issues have led the UN Special Rapporteur on the right to food to recommend a list of eleven principles for ensuring informed participation of local communities, adequate benefit sharing and the respect of human rights (De Schutter, 2009). This issue is elaborated with respect to rural areas, in Chapter 9 and livelihoods and poverty, in Chapter 13.

Extreme climate phenomena that may be harbingers of similar and more frequent events in a warmer world, already exact devastating consequences in some regions that extend well beyond country boundaries. A recent event that disrupted international trade and commodity flows was the severe 2010/2011 flooding in eastern Australia (Giles, 2011; Queensland Floods Commission of Inquiry, 2012; and see Chapter 25), which combined with damaging cyclones in Queensland and Western Australia curtailed numerous mining operations and damaged transportation networks, leading to declines in both thermal and metallurgical coal exports (by 31% and 19%, respectively, relative to the previous quarter – ABARES, 2011) with a sharp rise in their monthly price between November 2010 and January 2011 (Index Mundi, Coal). The severe weather was the primary factor contributing to a fall in Australian GDP of 1.2% during January-March 2011 compared with a rise of 0.7% in the preceding three-month period (Australian Bureau of Statistics, Australian National). Other examples of how extreme climate events can affect international trade are reported by Oh and Reuveny (2010) and Handmer et al. (2012).

21.4.1.4. International Transactions as Instruments of Regional Climate Policy

International policies to curb climate change and to adapt to its impacts, are increasingly looking to cross-border mechanisms to encourage action (and see Chapters 14-17). The European Union Emissions Trading System (EU ETS) is the first and largest international scheme for the trading of greenhouse gas emission allowances, covering some 11,000 power stations and industrial plants in 30 countries and accounting for almost half of the EU's CO_2 emissions and 40% of its total greenhouse gas emissions (European Commission, 2012). The Clean Development Mechanism (CDM) allows industrialised countries (Annex B Parties, cf. Supplementary material) to invest in emission-reduction projects in developing countries, which earn certified emission reduction (CER) credits, each equivalent to one tonne of CO_2. These CERs can be traded and sold to meet part of the emission reduction targets of the Annex B Parties under the Kyoto Protocol.

21.4.2. Human Migration

There has been considerable debate in recent years around the postulate that anthropogenic climate change and environmental degradation could lead to mass migration (Perch-Nielsen *et al*., 2008; Feng *et al*., 2010; Warner, 2010; Black *et al*., 2011; Government Office for Science, 2011; Assan and Rosenfeld, 2012). The issue is treated at length in Chapters 8, 9, 12 and 13 of Part A, so only a few aspects are touched on here, to highlight the growing significance of migration in all regions of the world.

Four possible pathways through which climate change could affect migration are suggested by (Martin, 2009):

1) Intensification of natural disasters
2) Increased warming and drought that affects agricultural production and access to clean water
3) Sea-level rise, which makes coastal areas and some island states increasingly uninhabitable
4) Competition over natural resources, leading to conflict and displacement of inhabitants.

Abundant historical evidence exists to suggest that changes in climatic conditions have been a contributory factor in migration, including large population displacements in the wake of severe events such as Hurricane Katrina in New Orleans, Louisiana in 2005 (Cutter *et al*., 2012), Hurricane Mitch in Central America in 1998 and the northern Ethiopian famines of the 1980s (McLeman and Smit, 2006). However, the evidence is not clear cut (Black, 2001), with counter examples also available of migration being limited due to economic hardship (e.g. during the Sahel drought of the mid-1980s in Mali – Findley, 1994).

The spatial dimension of climate-related migration is most commonly internal to nations (e.g. from affected regions to safer zones – Naik, 2009). In this context it is also worth pointing out that internal migration for other (predominantly economic) reasons may actually expose populations to increased climate risk. For instance, there are large cities in developing countries in low elevation coastal zones that are vulnerable to sea level rise. Increased migration to these cities could exacerbate the problems with the migrants themselves being especially vulnerable (Nordås and Gleditsch, 2007; UNFPA, 2007).

Migration can also be international, though this is less common in response to extreme weather events, and where it does happen it usually occurs along well established routes. For example, emigration following Hurricane Mitch tripled from Honduras and increased from Nicaragua by 40%, mainly to the southern States of the US – already a traditional destination for migrants, and was aided by a relaxation of temporary residency requirements by the United States (Naik, 2009).

The causal chains and links between climate change and migration are complex and can be difficult to demonstrate (e.g., Perch-Nielsen *et al*., 2008; Piguet, 2010; Tänzler *et al*., 2010; ADB, 2012; Oliver-Smith, 2012), though useful insights can be gained from studying past abandonment of settlements (McLeman, 2011). Thus projecting future climate-related migration remains a challenging research topic (Feng *et al*., 2010). There are also psychological, symbolic, cultural and emotional aspects to place attachment, which are well documented from other non-climate causes of forced migration, and are also applicable to cases of managed coastal retreat due to sea-level rise (e.g., Agyeman *et al*., 2009). Furthermore, forced migration appears to be an emerging issue requiring more scrutiny by governments in organising development co-operation, and to be factored into international policy making as well as international refugee policies. For example, it has been suggested that the National Adaptation Plans of Action (NAPAs) under the UNFCCC, by ignoring transboundary issues (such as water scarcity), and propounding nationally-orientated adaptation actions (e.g. upstream river management, to the detriment of downstream users in neighbouring countries), could potentially be a trigger for conflict, with its inevitable human consequences. Moreover, currently there is no category in the United Nations High Commission for Refugees classification system for environmental refugees, but it is possible that this group of refugees will increase in the future and their needs and rights will need to be taken into consideration (Brown, 2008). The Nansen Initiative, put forward jointly by Norway and Switzerland at a 2011 ministerial meeting, pledges "to cooperate with interested states and relevant actors, including UNHCR, to obtain a better understanding of cross-border movements provoked by new factors such as climate change, identify best practices and develop a consensus on how best to protect and assist those

affected ", and may eventually result in a soft law or policy framework (Kolmannskog, 2012 environmental). However, migration should not always be regarded as a problem; in certain circumstances where it contributes to adaptation (e.g. through remittances) it can be part of the solution (Laczko and Aghazarm, 2009).

21.4.3. Migration of Natural Ecosystems

One of the more obvious consequences of climate change, is the displacement of biogeographical zones and the natural migration of species (see Chapters 4 and 6). General warming of the climate can be expected to result in migration of ecosystems towards higher latitudes and upward into higher elevations. Species shifts are already occurring in response to recent climate changes in many parts of the world (Rosenzweig *et al.*, 2008), with average poleward shifts in species' range boundaries of 6 km per decade being reported (Parmesan *et al.*, 2011).

Study of the estimated shifts of climatic zones alone can provide insights into the types of climatic regimes to anticipate under projected future anthropogenic climate change. By grouping different combinations and levels of climatic variables, it is possible not only to track the shifts in the zones in which they occur, but also to identify newly emerging combinations of conditions not found at the present day (novel climates) as well as combinations that may not survive global climate change (disappearing climates – Williams *et al.*, 2007). These analyses can help define what types of climatic niches may be available in the future and where they will be located. Such a spatial analogue approach (cf. Carter *et al.*, 2007) can delimit those regions that might currently or potentially (in the future) be susceptible to invasion by undesirable aquatic (e.g., EPA, 2008) or terrestrial (e.g., Mainka and Howard, 2010) alien species or alternatively might be candidates for targetting translocation (assisted colonisation) of species endangered in their native habitats (e.g., Brooker *et al.*, 2011; Thomas, 2011). However, there are many questions about the viability of such actions, including genetic implications (e.g., Weeks *et al.*, 2011), inadvertent transport of pests or pathogens with the introduced stock (e.g., Brooker *et al.*, 2011) and risk of invasiveness (e.g., Mueller and Hellmann, 2008).

The ability of species to migrate with climate change must next be judged, in the first instance, against the rate at which the climatic zones shift over space (e.g. Loarie *et al.*, 2009 – Figure 21-11). For projecting potential future species shifts, this is the most straightforward part of the calculation. In contrast, the ecological capacity of species to migrate is a highly complex function of factors, including their ability to:

- Reproduce, propagate or disperse
- Compete for resources
- Adapt to different soils, terrain, water quality and daylength
- Overcome physical barriers (e.g. mountains, water/land obstacles)
- Contend with obstacles imposed by human activity (e.g. land use, pollution or dams).

[INSERT FIGURE 21-11 HERE
Figure 21-11: The velocity of shifting climatic zones due to climate change based on the average of 16 global climate models for an A1B emissions scenario and temporal gradients computed for 2050-2100. (Loarie et al., 2009).]

Conservation policy under a changing climate is largely a matter of promoting the natural adaptation of ecosystems, if this is even feasible for many species given the rapidity of projected climate change. Studies stress the risks of potential mismatching in responses of co-dependent species to climate change (e.g., Schweiger *et al.*, 2012) as well as the importance of maintaining species diversity as insurance for the provision of basic ecosystem services (e.g., Traill *et al.*, 2010; Isbell *et al.*, 2011). Four priorities have been identified for conservation stakeholders to apply to climate change planning and adaptation (Heller and Zavaleta, 2009): (i) regional institutional coordination for reserve planning and management and to improve landscape connectivity; (ii) a broadening of spatial and temporal perspectives in management activities and practice, and actions to enhance system resilience; (iii) mainstreaming of climate change into all conservation planning and actions; and (iv) holistic treatment of multiple threats and global change drivers, also accounting for human communities and cultures. The regional aspects of conservation planning transcend political boundaries, again arguing for a regional (rather than exclusively national) approach to adaptation policy. This issue is elaborated in Chapters 4 and 14.

21.4.4. Hotspots

Hotspots is an approach that has been used to indicate locations that stand out in terms of impacts, vulnerability or adaptive capacity (or all three). The approach exists in many fields and the meaning and use of the term hotspots differs. The term typically relates to a geographical location, which emerges as a concern when multiple layers of information are compiled. For example, the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change Agriculture and Food Security (CCAFS) mapped hotspots of food insecurity and climate change in the tropics (Ericksen et al, 2011). Other studies look at how climate change can influence disease risk (de Wet et al 2001), extinctions of endemic species (Malcolm et al 2005), and disaster risk (Dilley 2006). The purpose of the hotspots is to set priorities for policy action and for further research (de Sherbinin, submitted; Dilley 2006, Ericksen et al 2011, see www.climatehotmap.org).

Hotspots generally refers to a geographical location, but could also be used to refer to a topic, such as a type of ecosystem or farming system (eg. biofuels), a style of armed conflict (eg. guerrilla warfare) or seasonally distributed diseases (eg. malaria). This bends the definition of 'spot' but reflects the same approach: that certain circumstances result in certain levels of exposure or sensitivity to climate change. Below are some ways in which hotspots are used:

Climate Change: A climate change hotspot can describe (a) a region for which potential climate change impacts on the environment or different activity sectors can be particularly pronounced or (b) a region whose climate is especially responsive to global change (Giorgi 2006). Since the AR4, a number of studies attempted to identify "Climate change Hotspots" at subcontinental scale following the latter definition. For example, Giorgi (2006), Diffenbaugh et al. (2008), Giorgi and Bi (2009), Xu et al. (2009) and Diffenbaugh and Scherer (2011) used different regional climate change indexes including changes in mean and interannual variability of temperature and precipitation to calculate late 21st century climate change "hot-spots" based on the CMIP3 ensemble accounting for multiple GCMs, scenarios and realizations. Among the most prominent hot-spots identified were the Mediterranean Basin, Central America, Central Africa, the Northern high latitude regions, the southwestern United States, Southeast Asia and the Tibetan Plateau. A new climate change hot-spot analysis of the CMIP5 ensemble was carried out by Diffenbaugh and Giorgi (2012), who extended the methodology of Giorgi (2006) and Diffenbaugh et al. (2008) by adding metrics of seasonal extremes and considering the temporal evolution and emergence of hotspots (Figure 21.12). They found that the Amazon, the Arctic, the Sahel and tropical West Africa, and the Tibetan Plateau are persistent regional climate change hotspots which emerge early in the 21st century of the RCP8.5 forcing pathway and persist throughout the rest of the century, suggesting that they are robust to varying levels of global warming. Areas of southern Africa, the Mediterranean, and Central America/western North America also emerged as prominent regional climate change hotspots but mostly in response to high levels of forcing. This contrasting persistence and emergence of hotspots in response to increasing radiative forcing highlights the relevance of regional climate heterogeneity for climate change mitigation and adaptation strategies. Others have defined climate change hotspots as locations where impacts of climate change are 'well pronounced and well documented' (UCS 2011). De Sherbinin (submitted) notes that because hotspots often overlay projections of climate change with current vulnerability, there is a disconnect in timescales.

[INSERT FIGURE 21-12 HERE
Figure 21-12: The relative aggregate climate change between the 1975-2005 period and the 2010-2039, 2040-2069 and 2070-2099 periods of RCP8.5. The aggregate climate change is calculated using the Standard Euclidean Distance (SED) across the 28-dimensional climate space formed by 7 climate variables in each of 4 seasons. The absolute values of change in each variable are normalized to the maximum global absolute value prior to calculating the SED. The SED values are then normalized to the maximum global SED value. Only land grid points north of 60°S are used in the normalizations (From Diffenbaugh and Giorgi 2012).]

Biodiversity and Conservation: A biodiversity hotspot – the original use of this concept – is a recognised unit of analysis for guiding policy and investment decisions, developed by Meyers (1988). It refers to a region that is biologically diverse and typically under some sort of threat from human activity, climate change, or other drivers.

Health and Disease: Hotspots of disease can describe incidence rates, death rates, areas where certain viruses are likely to emerge, among other things. They can be coupled to climate change, biodiversity change, population growth, human-animal proximity, or to other drivers. A study on emerging infectious diseases (EIDs) identified hotspots as regions where new EIDs are likely to originate, in order to guide decisions makers where to allocate global resources to pre-empt, or combat, the first stages of disease emergence (Jones et al 2008).

Disasters: Disasters hotspots are identified as geographic areas that are most vulnerable to hazards (Dilley et al 2006). The purpose of disasters hotspots is to encourage development agencies and policy makers to incorporate disaster risk management into investment plans and decisions (Arnold et al 2005).

Food production, Food security: Areas of food production that are affected by pressures such as urbanisation, environmental degradation, water scarcity or climate change can be identified as hotspots of food insecurity, such as by CGIAR CCAFS (Ericksen et al 2011). Similarly, adverse implications of agriculture on environment have been described as 'agri-environmental hotspots'. FAO (2010) defines agri-environmental hotspots as 'locations where human activities are detrimental to the sustainability of an ecosystem or the human activities depending on it'. The rationale for identifying such hotspots is that 'they may gradually evolve into extremely tense socio-economic situations associated with a severe degradation of the natural resources base and food security' (FAO 2010). Fraser et al (2013) combine hydrological modelling with quantitatively modelled adaptive capacity (defined as the inverse of sensitivity to drought) to identify vulnerability hotspots for wheat and maize.

21.5. Critical Analysis of Approaches to Regional Impacts, Adaptation, and Vulnerability Studies and Their Uncertainties

Assessing climate vulnerability or options for adapting to climate impacts in human and natural systems requires an understanding of all factors influencing the system and how change may be effected within the system or applied to one or more of the external influencing factors. This implies the need, in general, for a wide range of climate and non-climate information and then determining how this may be used to enhance the resilience of the system. Previous sections have defined the context in which these systems operate, synthesized key regional and cross-regional knowledge and issues. This section focuses on advances in the methods and information that underpin these findings, initially examining methods to study vulnerability and adaptation and assess impacts. This is followed by assessments of new information on, and thinking related to: (a) baseline and recent trends in factors needed to assess vulnerability and define impacts baselines; and (b) future scenarios used to assess impacts, changes in vulnerability and options for adaptation; and then assessment of the credibility of the various types of information presented.

21.5.1. Vulnerability and Adaptation Analyses

Multiple methodologies exist for assessing vulnerability and adaptive capacity (Schipper et al 2010, UNFCCC 2008) and many have now become well-established approaches. Choice of method is influenced by objective and starting point (see Table 21-3) as well as the type of information available. Qualitative assessments require different inputs from quantitative assessments. Qualitative information cannot always be translated to quantitative information, and vice versa, yet both qualitative and quantitative approaches can be used to answer the same questions.

The comparison of vulnerability and adaptive capacity across regions requires some common baseline from which to judge relative levels of vulnerability and adaptive capacity – a type of measurement. Measuring adaptive capacity has not been explored in the same way, and often adaptive capacity is assumed to be a component of vulnerability (based on the vulnerability definition in IPCC 2001). Qualitative and quantitative studies are used to identify why people are vulnerable and how, and are typically the basis for determining strategies for reducing vulnerability and adapting to climate change. Indicators have been used to make this comparison. This section reflects briefly on indicators.

Several attempts at developing vulnerability indicators and indices have been made (Birkmann et al. 2011; Chen et al. 2011; Barr et al 2010; Cardona, 2007; Luers et al 2003; Lawrence *et al.,* 2003, Villa and McLeod, 2002, Downing *et al*. 2001, Atkins *et al.,* 2000; Moss *et al*. 1999). Representation of vulnerability on a map or through an index is the most common way to show global vulnerability information and requires quantification of selected variables in order to measure them against a selected baseline, even though quantification of some qualitative information may not be possible (Hinkel, 2011; Edwards et al, 2007; Luers et al 2003,). Maps of vulnerabilities where hazards or projected climate change impacts are overlain with population density suggests that everyone has an equal probability of being affected by a hazard or by climate change impacts, ie. that everyone is equally at risk. Vulnerability is differentiated according to factors such as gender, age, livelihood or access to social networks (Cardona et al 2012; Wisner et al 2005), which can be a challenge to incorporate into indicators, and therefore choice of indicators of or proxies for vulnerability will determine what the result looks like. One approach that is used to create regional comparisons is an index approach that measures different variables to create indicators of vulnerability. The index is the composite of several normalised indicators (Rygel et al 2006, Adger et al 2004). The approach has been critiqued extensively because giving different weights to the indicators depends on expert opinion and this can result in different countries appearing more or less vulnerable, as Fuessel (2010) found in reviewing different vulnerability maps. Lack of full understanding of what drives vulnerability means that indicators can give misleading or incorrect information about vulnerability (Böhringer and Jochem, 2007).

Luers et al (2003) propose the idea of ex-post measure of vulnerability, using the number of people killed in a storm as an indicator that they were vulnerable. A deductive analysis of the situation would suggest that they were killed because (a) they were exposed to the storm, (b) they were sensitive to the storm, (c) they had low capacity to escape the storm or (d) the storm had a very high impact. However, a low impact storm could also result in deaths if the people were especially sensitive or exposed. Their deaths could also simply be explained by being in the wrong place at the wrong time, which suggests that ex-post analysis can indicate only the state of vulnerability of the people killed at the moment they were killed, and not anything else. Conversely, an ex-ante analysis of vulnerability to a storm might suggest that old people, people who will not want to evacuate their houses because they do not want to risk losing their assets (such as livestock) or people who have a lack of knowledge of where to go and what to do in an emergency, would be the most sensitive and exposed. Even with these characteristics, the outcome does not necessarily lead to death, since they could also be rescued, their area could be unaffected by the storm, or they could survive anyway. In other words, identifying a single characteristic or even several may not give a sufficient picture of vulnerability for decision making, even on a local level.

Vulnerability indicators developed to date have been unable to reflect the dynamic nature of the various variables used as indicators. This is illustrated in the case of the (in)ability to characterise how the selected indicators contribute to determining vulnerability over time. Importantly, the relative importance of the indicator may change from season-to-season (eg, access to irrigation water) or gradually or rapidly become obsolete. Hinkel's (2011) review of literature on vulnerability indicators suggests that vulnerability has been confused as a proxy for unsustainable or insufficient development, which means that simple measurements are seen as sufficient to tell a story about vulnerability. Hinkel (2011) suggests that the simplification of information to create vulnerability indicators is what limits the utility of vulnerability indicators.

Adaptation is considered to be tightly linked with development (Adger et al 2003b, Schipper 2007) and a significant portion of adaptation approaches emerge from activities in developing countries. The metrics of adaptation is a topic of considerable interest for the purpose of funding prioritisation, monitoring progress in adjusting to climate change and identifying suitable adaptation options (IGES 2008).

Adaptation assessment as a process is described more extensively in chapters 2, 14, 15, and 17, and this section addresses the usefulness of indicators for understanding adaptation at a regional and global level. Most adaptation assessments rely on assessing adaptive capacity (Yohe and Tol 2002), based on some variables that are often transformed into indicators, success of implementation of adaptation projects (often also based on a set of indicators) or 'functions' that countries should follow to attain resilience (WRI 2009).

As a way of understanding adaptive capacity further, numerous types of indicator systems have been developed. These are used both to measure adaptive capacity as well as to identify entry points for enhancing it (Adaptation

Sub-Committee, 2011; Lioubimtseva and Henebry, 2009; Swanson et al., 2007; Adger and Vincent, 2005; Eriksen and Kelly, 2007) For example, the Global Adaptation Index, developed by the Global Adaptation Alliance (GAIN, n.d.) uses a national approach to assess vulnerability to climate change and other global challenges and compare this with a country's 'Readiness to improve resilience' (GAIN, n.d.) for the purpose of assisting public and private sectors to prioritise financial investments in adaptation activities.

Indicators can be a useful starting point for a discussion on what qualifies as an appropriate proxy for capacity, in order to determine what sort of factors act as barriers and drivers. When rooted in the poverty and livelihoods discourse on vulnerability (Chambers, 1989; Swift, 1989), proxies for capacity look very similar to indicators of development, despite the significant argument about the causal structure of vulnerability, which underscores that vulnerability is not the same as poverty (Chambers, 1989; Ribot, 1996). Resources may be for enhancing 'the capacity and endurance of the affected people to cope with adversities' (Ahmed and Ahmad 2000: 100), but equating vulnerability with poverty creates a false association between lack of development and lack of capacity (Magnan, 2010).

A special case of the use of indicators concerns the identification of hotspots. This is a concept used in numerous fields to describe locations that stand out as important for the analytical lens that is being applied (see section 21.4.4, above). The purpose of doing hotspot analysis varies across different fields, but they are typically the outcome of the combination of different sets of variables with a geographical reference. In climate change, hotspots are being used with increasing frequency to help distinguish priority locations for funding (de Sherbinin, submitted). The presentation of hotspots differs according to multiple factors, including the scale of analysis (from specific houses to entire ecosystems), the number of variables examined (two or more), whether the information refers to measured or projected hotspots. Hotspots can contrast with "cool spots", where the inverse situation can be found, and can be ranked when they are derived from numerical values (e.g., number of crimes committed). Hotspots are another way of comparing regions, and the subjective nature of ranking locations as more urgent for climate change investment than others is controversial and can be considered politically-motivated (Klein 2009). In part, this is also because the identification of hotspots raises important methodological issues, discussed earlier in this section, with regard to the limitation of using indicators to give an illustration that integrates impacts with qualitative dimensions of vulnerability. De Sherbinin (submitted) points out that hotspot maps are commonly used as communications tools, but the tentative nature and the on-going process of knowledge generation that they represent is frequently not understood by the audience, who see the maps as a description of how things are or will be.

Certain areas are considered hotspots because of their regional or global importance. These can be defined by population size and growth rate, contributions to regional or global economies, productive significance (e.g., food production) as well as by disaster frequency and magnitude, and projected climate change impacts. Variables identified to represent these issues can be controversial, and relationships between variables may not always be fully understood. For instance, the CCAFS hotspot map introduced in section 21.4.4 uses stunted growth as a proxy for food insecurity (Ericksen et al 2011), but other variables could also have been selected, and could have resulted in different locations being identified as hotspots (Füssel, 2009). Scale matters in representing hotspots and will look differently on a global scale than on a finer scale (Arnold et al., 2006).

21.5.2. Impacts Analyses

In recent years, as adaptation considerations have risen up the policy agenda, there has been increased scrutiny of the methods and tools applied in impact assessment, especially quantitative models that are used to project the biophysical and socio-economic impacts of future climate change (see chapter 2), but also encompassing qualitative methods, including studies of indigenous knowledge (Galloway McLean, 2010, and see chapter 12). In an advance from previous assessments, different types of impact models are now being applied for the first time in many regions of the world. This is largely due to burgeoning international development support for climate change vulnerability and adaptation studies (Fankhauser, 2010). It is also related to a surge of interest in regional economic assessments in the wake of the Stern review (Stern, 2007) as well as to the evolution of climate models into earth system models that incorporate a more realistic representation of land surface processes (Flato *et al.*, in prep.) and their increased application to study hydrological (chapter 3), ecophysiological (chapter 4) and cryological (chapter 28) impacts.

21.5.2.1. Framing of Impact Studies

Potential impacts have been simulated for single as well as multiple sectors, at spatial scales ranging from site or household to global, and over a range of temporal scales and time horizons (Table 21.3). A majority of impact studies still follow the conventional approach described in section 21.2.3 (left hand side in Table 21-3), whereupon future impacts are modelled based on a set of assumptions (scenarios) about future climate and socioeconomic conditions. However, an increasing number of impact studies are being undertaken that follow a "socio-institutional" approach to adaptation planning (Downing, 2012) as reflected on the right hand side of Table 21-3, which emphasises adaptive flexibility and climate resilience as an acknowledgement of the often intractable, "deep" uncertainties implicit in many projections of future change (e.g., Donley *et al*., 2012; Garrett *et al*., 2013; Gersonius *et al*., 2013).

Adaptation assessment is addressed in section 21.5.1, but it should be noted that impact modelling studies commonly treat aspects of adaptation as well, either explicitly as modelled options, or implicitly as built-in autonomous responses (Dickinson, 2007; White *et al*., 2011). Furthermore, with an anthropogenic signature being attributed to ongoing climate changes in many regions (Bindoff *et al*., in prep.), and with growing evidence that these changes are having impacts on natural and human systems in many more regions of the world than reported in the AR4 (chapter 18, and see Rosenzweig and Neofotis, in press), there is now a real possibility in some regions and sectors to test the projections of impact models against the observed impacts of recent climate change (e.g., Araújo *et al*., 2005; Barnett *et al*., 2008; Lobell *et al*., 2011), which is also an essential element in the attribution of observed impacts (see chapter 18).

21.5.2.2. Uncertainties Attributable to Future Climate Projections

Much of the literature regarding uncertainty in impacts analyses has focused on the uncertainties in impacts that result from the uncertainties in future climate (Mearns et al., 2001a; Carter et al., 2007), and this literature continues to grow since AR4, particularly in the realm of agriculture and water resources (e.g., Wetterhall et al., 20011; Ferrise et al., 2011; Ficklin et al., 2012; Littell et al., 2011, Osborne et al., 2013), but also in other areas such as flood risk (Ward et al., 2013). Furthermore, research has moved forward to establish which uncertainties about future climate are most important to the resultant uncertainties about crop yields (e.g., Lobell and Burke, 2008). These uncertainties regarding future resources have now been applied to adaptation studies as well (Howden et al., 2007).

The use of a greater number of climate scenarios either from global or regional models is now found in many more studies. For example, in the area of impacts of climate change on water resources a number of studies have used more global models (Gosling et al., 2010; Bae et al., 2011; Arnell, 2011) or ensembles of regional climate models (Olsson et al., 2011), and thus present estimates of impact for between 10-25 different climates for a given emissions scenario. The use of probabilistic quantification of climate uncertainties has produced estimates of probabilities of changes in future resources such as agriculture and water (e.g., Watterson and Whetton, 2011; Tebaldi and Lobell, 2008). Some studies have developed probability distributions of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009).

Nobrega et al. (2011) apply a number of pattern-scaled GCMs to study the impacts of climate change on water resources in the Rio Grande Basin in Brazil. They used 6 different GCMs and 4 different SRES emissions scenarios and applied them to a large-scale hydrologic model, and found that choice of GCM was the major source of uncertainty in terms of river discharge. Through the CLARIS project (Menendez et al., 2010) multi-regional model climate change scenarios over South America will soon be used for a wide range of climate change impacts studies (e.g., Dengue fever, Degallier et al., 2010).

21.5.2.3. Uncertainties Attributable to Impact Models

With an ever-increasing number of projections of future climate change impacts appearing in the literature, and considering the unprecedented rate and magnitude of climate change projected for many regions, some authors have begun to question both the robustness of the models being applied (e.g., Heikkinen *et al.*, 2006; Fitzpatrick and Hargrove, 2009; Watkiss, 2011a) as well as the methods used to represent key uncertainties in model projections (e.g., Arnell, 2011; Rötter *et al.*, 2011; White *et al.*, 2011). This may reflect a relative low level of co-ordinated activity in the testing and intercomparison of impact models since the mid-1990s, following earlier efforts in the International Geosphere Biosphere Programme (e.g., Kabat *et al.*, 1995; VEMAP Members, 1995; Jamieson *et al.*, 1998) and other notable exceptions (e.g., Mearns et al., 2001b; Tebaldi and Lobell, 2008). However, in recent years there has been a strong resurgence of interest and activity, with several prominent international research efforts initiated, including the Agricultural Model Intercomparison and Improvement Project, involving crop and economic models at different scales (AgMIP – Rosenzweig *et al.*, 2013), the Carbon Cycle Model Intercomparison Project (C^4MIP) and its follow up (Friedlingstein *et al.*, 2006; Sitch *et al.*, 2008; Arora *et al.*, 2013) and the Water Model Intercomparison Project (WaterMIP – Haddeland *et al.*, 2011). Modelling groups from these projects are also participating in the Inter-Sectoral Impact Model Intercomparison Project, which is focusing initially on intercomparing global impact models for agriculture, ecosystems, water resources, health and coasts under RCP- and SSP-based scenarios (see Box 21-1), but will also consider regional models in a second phase of work (ISI-MIP – Schiermeier, 2012).

For example, in AgMIP preliminary results looking at five different wheat models at a site in Mexico indicate that the results for projections of yield to the mid-21st century are more sensitive to the differences in the crop models than to the differences among the different global climate models used (Rosenzweig et al., 2013). WaterMIP compared five global hydrologic and six land surface models to determine the uncertainty across these models in a climate change context for hydrological variables such as runoff and evapotranspiration. Results comparing the models for an observed period indicated substantial differences in the models' estimates in these key parameters (Haddelenad et al., 2011).

21.5.2.4. Effect of Combined Uncertainties

As is standard practice in climate modelling, a growing number of researchers are now applying multiple impact model and perturbed parameter ensemble approaches to future projections (e.g., Araújo and New, 2007; Jiang *et al.*, 2007; Palosuo *et al.*, 2011), usually in combination with ensemble climate projections treated discretely(e.g., New *et al.*, 2007; Graux *et al.*, 2013; Tao and Zhang, 2013) or probabilistically (e.g., Luo *et al.*, 2007; Fronzek *et al.*, 2009; Børgesen and Olesen, 2011; Ferrise *et al.*, 2011; Wetterhall *et al.*, 2011).

21.5.2.5. Evaluating the Robustness of Impact Models

Drawing inspiration from more than two decades of internationally co-ordinated efforts by climate modellers in the Atmospheric (AMIP) and then Coupled (CMIP) Model Intercomparison Projects (Gates *et al.*, 1998; Meehl *et al.*, 2005; Taylor *et al.*, 2012), these new impact MIPs, and other initiatives like them, have the common purpose of mobilising the research community to address some of the long-recognised but pervasive problems commonly encountered in climate change impact modelling. A sample of recent papers illustrate the variety of issues being highlighted, including forest model typology and comparison (Medlyn *et al.*, 2011), crop pest and disease modelling and evaluation (Sutherst *et al.*, 2011; Garrett *et al.*, 2013), modelling responses to extreme weather events (Lobell *et al.*, 2010; Asseng *et al.*, submitted), field experimentation for model calibration and testing (Long *et al.*, 2006; Craufurd *et al.*, 2013) and data quality considerations for model input and calibration (Lobell, 2013). Greater attention is also being paid to methods of economic evaluation of the costs of impacts and adaptation. Cost estimates have been reported at scales ranging from global (e.g., UNFCCC, 2007; Nelson *et al.*, 2009; Parry *et al.*, 2009; Fankhauser, 2010; Füssel, 2010; Patt *et al.*, 2010), through regional (e.g., EEA, 2007; World Bank, 2010; Ciscar *et al.*, 2011; Watkiss, 2011b), to national (SEI, 2009; GCAP, 2011) and local level (e.g., Perrels *et al.*, 2010).

21.5.3. Scenario Development and Application

21.5.3.1. Baseline Information and Context – Current State and Recent Trends

This section deals with defining baseline information relevant to the assessment of climate change vulnerability, climate change impacts and adaptation to climate change. Baseline here means the reference state or behaviour of a system, e.g. the current biodiversity of an ecosystem, or the reference state of factors (such as climate elements or agricultural activity) which influence that system (see also Glossary entry). In the pure climate context, the phrase pre-industrial baselines is used to define the (reference state of the) climate prior to changes in the atmospheric composition (from its baseline pre-industrial state), for example when the UNFCCC defines a reference for measuring global average temperature rises. An historical baseline refers to climate of a particular period, e.g. a WMO climate normal period such as 1961-1990 as a reference to define climate changes in recent decades, and if derived from a climate model then the model would include consistent changes in atmospheric composition. In an adaptation context, a baseline could be the impacts on a system under a given amount of climate change prior to changes in non-climate factors (e.g. improved early warning systems, modified infrastructure) aimed at reducing the impacts. This section does not consider methods for calculating baselines involved in assessing vulnerability of, impacts in and adaptations to systems – but methods for deriving the information on climatic and non-climatic factors used to calculate these baselines.

There are several important properties of baselines to consider when assessing methods to derive relevant information. Defining a reference state sufficiently well that it provides for a good measure of a system's vulnerability or for testing whether significant changes have taken place often requires that much of the variability of the system needs to be captured. Thus the information used to establish this reference state must account for the variability of the factors influencing the system; in the case of climate factors often this requires 30 years of data and sometimes substantially more (e.g. Kendon et al., 2008). Also the temporal and spatial properties of the system under investigation will influence the information required to establish a reliable baseline. Many systems operate at or depend on high resolution information, for example the high spatial resolution of urban drainage systems or organisms within an ecosystem sensitive to temperature extremes require information at the sub-daily time-scale.

Clearly, in defining baselines for assessing climate change impacts, vulnerability or adaptation, a wide range of information will be required as the systems being studies generally comprise interacting physical and human components influenced by climatic and non-climatic factors. For example the assessment of options to respond to river flooding will require information on some or all of the following: past and future rainfall/river flow sequencing and river channel modifications; likelihood of riverside development; viability of property insurance; regional or national finances; effectiveness of relevant institutions. In this case information is required on climate and other physical aspects of the system as well as social and economic factors, and this will generally be so. The rest of this section then assesses methods to derive climatic and then non-climatic information relevant to establishing these baselines and the reliability of this information.

21.5.3.1.1 Climate baselines and their credibility

Fundamental to the study of climate change impacts is to establish an "impact baseline", the behaviour of the system under a reference climate. The baseline information defining this reference climate may be derived from either or a combination of observations or models, with the spatial and temporal resolution generally prescribed by the source, and the choices generally depending on the application. For example Challinor et al. (2004) use observed weather inputs at the daily timescale and coarse spatial resolution with a crop model to demonstrate its ability to simulate a realistic range of yields under historical climate variability to motivate using the model to estimate quantitatively the effect on yields of perturbed climates (e.g. Challinor et al., 2006). Arnell et al. (2003) used a range of climate baselines to study the effect of different choices on the characteristics and ranges the impacts (and paid less attention to the validation of the impacts baselines). In a further example Bell et al., (2009) use high quality observed data at daily timescale and 5 km resolution to demonstrate the ability of a river flow model to simulate an accurate baseline over a 1km river network in order to establish confidence in the impacts model. This is then used with less accurate

climate model-derived baselines that are then compared with results when using climate-model derived futures (Bell et al., 2012). In this case the impacts model is being used with plausible time-series of climate variables to derive realistic (though not necessarily accurate) high resolution baseline and future river flows and thus ranges of climate change impacts which can be considered realistic responses to the imposed climate perturbations. In a more comprehensive study of impacts of climate change in selected UK rivers, Kay and Jones (2012) used different baselines from the UKCP09 scenarios (Murphy et al., 2009) and noted that the changes were similar when using either weather generator or RCM baseline information. However, a greater range of projected changes resulted when using high time-resolution (daily rather than monthly) information (Figure 21-13), underscoring the importance of including the full spectrum of climate variability when assessing climate impacts.

[INSERT FIGURE 21-13 HERE
Figure 21-13: The range of percentage change in flood peaks for nine UK catchments at the a) 2-year and b) 20-year return period. Box-and-whisker plots are used to summarise results when using 10,000 UKCP09 Sampled Data (Murphy et al. 2009) change factors (red) and 100 sets of UKCP09 current and future Weather Generator time-series (cyan). Also plotted, are the results when using 11 sets of RCM-derived change factors (red crosses) and when using 11 sets of RCM current and future times-series (green rectangles). The box delineates the 25^{th}-75^{th} percentile range and the whiskers the 10^{th}-90^{th} percentile range, with the median (50^{th} percentile) shown by the line dividing the box. Additional markers outside the whiskers indicate the minima and maxima, if within the plotted range of -50 to +100. The points derived from the RCM results are joined for the corresponding members of the RCM ensemble (grey lines), and the medians for these methods are shown by black horizontal bars.]

These examples show that a good description of the baseline climate, i.e. in general including information on its variability on timescales of days to decades, is important for developing the reference state or behaviour of a climate-sensitive system for determining impacts on or the vulnerability of the system. This has motivated significant efforts to enhance the quality, length and homogeneity of observed climate records (also important for monitoring, detecting and attributing observed climate change, AR5-WG1 Chapter 2-5 and 10)) and to make these data more easily available. This has included derivation of new observational datasets such as APHRODITE (a gridded rain-gauge based dataset for Asia, Yatagai, et al., 2012), coordinated analysis of regional climate indices and extremes by CLIVAR's ETCCDI (http://www.clivar.org/organization/etccdi, see e.g. Zhang et al., 2011) and data rescue work typified by the ACRE initiative (Allen et al., 2011) which has resulted in analysis and digitization of many daily or sub-daily weather records from all over the world. For some datasets error estimates have been developed (e.g. Morice et al., 2012 for the HadCRUT near-surface temperature record) and for others such as precipitation, increased focus on improving existing datasets such as GPCC (Rudolf et al., 2011) and developing new ones (e.g. TRMM (Huffman et al., 2010) or APHRODITE, Yatagi et al.; 2012) enables observational uncertainty to be estimated. This allows us to more accurately quantify the amplitude of natural variability important for detecting trends or establishing impacts or vulnerability baselines.

Another area of significant progress has been in the development of improved and new global reanalyses. These use weather forecast models constrained by observations from across the globe and available through a period of time to reconstruct the evolution of the weather over the globe. A significant new development in this field has been the use of digitized surface pressure data from ACRE by the 20^{th} Century Reanalysis (20CR) project (Compo et al., 2011) to reconstruct the global evolution of the weather from 1871 to present day. 20CR provides the basis for, at any location, estimating historical climate variability from the sub-daily to the multi-decadal timescale (Figure 21-14) and hence developing robust estimates of the baseline sensitivity of a system to the climate and addressing related issues such as establishing links between historical climate events and their impacts. Other advances include new reanalyses (http://reanalyses.org/) with a focus on developing higher quality reconstructions for the more recent period. They include a new European Centre for Medium Range Weather Forecasts (ECMWF) Reanalyses (ERA) dataset, ERA-Interim (Dee et al., 2011) for the period 1979-2011, the NASA Modern Era Reanalysis for Research and Applications (MERRA), 1979-present (Rienecker et al., 2011), the NCEP Climate Forecast System Reanalysis (CFSR), 1979-Jan 2010 (Saha et al., 2010) and regional reanalyses such as the North American Regional Reanalysis (NARR) (Mesinger et al., 2006) and EURO4M (http://www.euro4m.eu/).

Variables from the first generation of reanalyses often contained discontinuities in time (often resulting from changes in the observations they used) thus clearly were not suitable for defining trends (Thorne and Vose, 2010)

and needed to be used with caution to define climate baselines. In addition, reanalyses combine observations, generally with global coverage, with models and thus those outputs less directly constrained by the observations are subject to model error. For example, precipitation derived from the ECMWF's ERA15 and ERA-40 reanalyses did contain significant biases which have been much reduced in the more recent ERA-Interim dataset (Dee et al., 2011). As with recent efforts on observational datasets, the production of several reanalyses from different international centres (AR5-WG1 Box 2.3) means that the uncertainty in their of climate baselines can be estimated. In the case of 20CR (Compo et al., 2011) a 56 member ensemble of reconstructions was calculated. This is useful in assessing the credibility of the reanalysis in the regions in the early part of the 140-year reconstruction where there were sparse (or no) observations and also to give an estimate of the inherent uncertainty in detail provided by these reanalyses even where there are good observations.

[INSERT FIGURE 21-14 HERE
Figure 21-14: Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann etal. (2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis and model sources: statistical reconstructions of the PWC, the PNA and the NAO, see Brönnimann et al. (2009) for details, (all cyan); 20CR (pink); NCEP–NCAR reanalyses (NNR; dark blue); ERA-40 (green); ERA-Interim (orange). The dark-grey dashed line and grey shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed seas-surface temperatures and sea-ice from the HadISST dataset (Rayner et al. 2003), see Brönnimann etal. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea-surface temperature and sea-ice alone and demonstrate that the reanalyses have significantly higher skill in reproduces these modes of variability.]

As noted in the introduction, the scale of the system being investigated often implies the need for high temporal and spatial resolution climate information, either observed or simulated, to calculate its baseline or reference behaviour. Observed high-resolution climate baselines are not available in many regions or for all variables required (e.g. Washington et al. 2006, World Weather Watch 2005). Even when datasets exist, they often only provide monthly mean data and thus lack temporal variability and often lack sufficient spatial resolution. The recent reanalyses provide globally complete and temporally detailed reconstructions of the climate of the recent past but generally lack the spatial resolution which would enable them to represent the fine details of weather events often important when modeling the response of systems sensitive to climate. However, they can be combined with either statistical or dynamical downscaling (see e.g. Maraun et al., 2010, AR5-WG1 Chapter 9) to provide higher resolution simulations of the variables required consistent with the (usually reasonably accurate estimate of the) large-scale drivers from the reanalyis. Available observations can then be used to estimate the error in the downscaled simulation.

An example of this methodology is given by Duryan et al., 2010 for West Africa who analyse results from nine regional climate models driven by ERA-Interim for the period 1990-2007 for a region encompassing West and much of Central Africa. Many models show significant biases (Figure 21-15) and thus may not be considered sufficiently accurate to provide the required additional detail on the climate baselines for the region. Advances in this area should be expected through the WCRP-sponsored Coordinated Regional Downscaling Experiment (CORDEX) project (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html and see Giorgi et al., 2009) with the initial experiment recommended being to apply the downscaling methods to the ERA-Interim over all land and enclosed sea areas using common domains for dynamical downscaling.

[INSERT FIGURE 21-15 HERE
Figure 21-15: Observed 1990-2007 annual precipitation climatology from GPCC (Rudolf et al., 2011), top left, and, in the remaining panels, related systematic errors in 9 individual regional climate model simulations driven by the ERA-Interim reanalyses (Dee et al., 2011) and in the multi-model ensemble mean (Duryan et al., 2010).]

Climate baseline information can also be derived directly from climate models, either global models or via downscaling of their outputs. Significant international activity on establishing the credibility of the climate simulations of these models is enabled through the coordination activities of the Coupled Model Intercomparison

Project (e.g. CMIP5, Taylor et al., 2009) and has shown improvements in the quality of this information since AR4 (AR5-WG1 Chapter 9). The issue raised above of credibility of climate information from a spatial resolution perspective is relevant here, though there has been some improvement since CMIP3/AR4 with many of the models now running at 100-150km resolutions. Again, this may be addressed by downscaling these simulations (which has been facilitated by improved data capture from the CMIP5 models for CORDEX, Giorgi et al., 2009) and the credibility of this information can be established by similar validation procedures (AR5-WG1 Chapter 9). In theory, one would expect that validation of a reanalysis downscaling should provide a more accurate picture of a models performance though this can be complicated by reanalysis errors (Cerezo-Mota et al., 2010) or differences between reanalyses (Mearns et al., 2012).

With downscaling providing climate baselines at high temporal and spatial resolutions, these can be used directly to assess the impacts of the projected high-resolution climate changes. Historically, the more usual approach has been to use observed baselines and then add climate changes derived from climate projections to these and then calculate the impact using this perturbation of the observed baselines. This was the only viable approach to take when high resolution input data were required to assess impacts or vulnerability and only coarse resolution GCM-based projections were available. Now high-resolution projections are becoming increasingly available both direct and perturbed baseline approaches can be used (see e.g. Kay and Jones, 2011). The direct approach has the disadvantage that the baseline climate will often contain significant errors and their influence on the calculated impact will need to be addressed. The perturbed baseline approach has the disadvantage that in order to calculate a plausible future climate accounting for the full detail of projected climate change the perturbations applied should account for changes in those aspects of climate variability that the system being studied is sensitive to (see e.g. Hawkins et al., 2013). Thus it is important to consider not just the quality of the baseline but what influence the choice of baseline may have on the assessment of vulnerability or the calculation of climate change impacts.

21.5.3.1.2. Non-climatic baselines and their credibility

Given the diversity of non-climatic influences on many climate-sensitive systems baseline information on a wide range of factors will often be required. For example agriculture, water resources, ecosystems and health are all affected by a diverse range of (non-climatic) physical factors and socio-economic influences. Example of physical factor are availability of irrigation systems for agriculture, effectiveness of disease prevention, atmospheric composition (e.g. affecting air quality or CO_2 availability for plant growth) and land-cover/use (e.g. defining the urban environment or availability of agricultural land). Relevant socio-economic factors include demography, level of social, educational and economic development, political/governance background and available technology. Thus to provide a comprehensive assessment of how or whether a climate-sensitive system can adapt to climate change it is necessary to assess its vulnerability in respect of all non-climatic factors that may influence it and information is required on the baseline state of these factors to enable the reference behaviour of a system to be established. (See also TAR WG2 Chapter 13 and AR4 WG2 Chapter 2.)

Significant work has been undertaken to collect and make this information available. For the socio-economic factors, local and national governments and international agencies (e.g. UN agencies, World Bank - http://data.worldbank.org/data-catalog) have been collecting data on the human-related factors for many decades and similarly information on technological developments is widely available. In some situations these factors are evolving quickly and the baseline is taken as the reference state at a particular point in time rather than aggregated over a longer period. In the case of the physical factors, information on many of these have been refined and updated as they are critical inputs to deriving the climate forcings in the Representative Concentration Pathways (RCPs, van Vuuren et al., 2011) used in the CMIP5 (Taylor et al., 2009) experiments. For example these included updated information on land-use change (Hurtt et al., 2011), atmospheric composition (Meinshausen et al., 2010) and aerosols (Grainer et al., 2011, Lamarque et al., 2011). Other aspects of the physical environment in many areas have been well-studied and detailed records are available (e.g. through improved satellite observations and observational processing or via research by international bodies e.g. FAO assessing agriculture and forestry systems). However, much like with climate observations, there are still areas of the world which are less well-observed where rescuing and/or making available old records of the physical environment is of significant value as is making new or more detailed observations.

Given the multi-stressor environment in which assessments of climate change vulnerability and adaptivity are being made, there needs to be consideration of multiple plausible non-climate futures. In this situation a future baseline can be defined, e.g. a given socio-economic scenario, to establish, along with future climate scenarios, a reference state of future vulnerability or adaptive capacity. This then allows the impact of alternative socio-economic futures, such as the story-lines associated with the Special Report on Emissions Scenarios (SRES, IPCC, 2000) and the new Shared Socio-economic Pathways (SSPs), on future vulnerability or adaptation options to be assessed.

A key step in assessing adaptation to climate change in a system is defining information on the non-climatic factors which influence its vulnerability: i.e. the importance of the non-climatic baseline information being assessed here is how it defines the baseline vulnerability of the system and so how changes in these factors can allow it to adapt to climate change, i.e. compensate for/take advantage of increased/reduced climate vulnerability. Given the diversity of climate-sensitive systems as explained above, it is not possible to assess methods for deriving all non-climatic baselines relevant to vulnerability and adaptation studies.

In some cases, this information will be able to be derived from available data sources and in other cases it will be deficient (e.g. in resolution) or missing. The rest of this section will concentrate on presenting several studies which demonstrate some of these cases as a guide to the importance of relevant non-climatic baselines and how they can be derived and interpreted.

The issue of establishing an appropriate non-climatic baseline, in this case in the physical environment, is illustrated in the example of a study of climate change impacts on flow in the River Thames in the UK. Despite increases in temperature and a major change in the seasonal partitioning of rainfall over the Thames basin there is no long-term trend in annual maximum flows over a 126 year series (Marsh 2004). In the 19th century summer rainfall was on average greater than in winter, a situation reversed by the end of the 20th century due to respectively negative and positive precipitation trends which would be expected to have influenced maximum flows. An investigation of the physical environment found that it had been significantly modified as part of river management activities with increases in channel capacity of 30% over 70 years leading to fewer floods in the lower Thames. In this case, establishing the current level of vulnerability of the Thames to flooding required a detailed investigation to determine the appropriate baseline for the physical factor (river channel capacity) influencing this vulnerability.

Another example involves a study of the potential for adaptation in response to projected climate change impacts on crop yields (Challinor et al., 2009). The relevant non-climatic factor in this case was technological, the availability of alternative crop varieties. Detailed field studies demonstrated that the current germplasm included varieties with a wide range of tolerance to higher temperatures (Badigannavar et al., 2002). This established an agricultural technology baseline which demonstrated the potential to reduce vulnerability in the system to compensate for the projected climate change impact.

The relevance of future baselines is demonstrated in the assessment of the economics of climate change as presented in the report of the same name, also known as the Stern report (Stern 2007). For example, a baseline of technological improvement was assumed in determining the costs of mitigation. Also, as noted by Mendelsohn (2007), it makes assumptions (i.e. defines a baseline) about future economic growth in order to establish the costs of projected impacts or damages. In such cases, applying variations from these baselines allows the sensitivity of the findings of such studies to the proposed future baselines to be tested.

21.5.3.2. Development of Scenarios and Projections

Since the AR4 there have been several new developments in the realm of scenarios and projections: 1) a new approach to the construction of global scenarios for use in climate change analysis, initiated with the development of representative concentration pathways (RCPs); 2) the development and application of a greater number of higher resolution climate scenarios from regional climate model simulations; and 3) further use of multiple scenario elements as opposed to use of climate change scenarios only and greater focus on multiple stressors. Scenarios of land-use change are also deserving of more attention and are also discussed below.

21.5.3.2.1. New approach to scenario development

For both the TAR and AR4, the main socio-economic and emissions scenarios used were derived from SRES (Nakicenovic et al., 2000). More recently a new approach to developing climate and socio-economic scenarios was adopted. This new approach changed the familiar linear structure, wherein socio-economic scenarios were constructed, these were used to calculate emissions through application of Integrated Assessment Models (IAMs), and from the concentration of greenhouse gasses and aerosols, climate models would simulate the climate response to the forcings. In the new approach, concentrations of greenhouse gases were developed first (Representative Concentration Pathways, Moss et al., 2010), which allowed the climate modeling work to proceed much earlier in the process. Different possible socio-economic pathways were to be determined later, and it was recognized that more than one socio-economic pathway could lead to the same concentrations of greenhouse gases and aerosols. The process of determining the socio-economic scenarios is ongoing (US NAS, 2010). Four different RCPs were developed, corresponding to 4 different levels of forcing (by 2100) based on watts/m2: RCP 8.5, 6.0, 4.5, and 2.6. These embrace the range of scenarios found in the literature, and they also include explicit stabilization strategies, which were missing from the SRES set. In addition, a set of Shared Socio-economic Pathways (SSPs) is being developed that would characterize a wide range of possible development pathways. More information on these scenarios may be found in Chapter 19 (Box 19-3) of WG2, the WG3 Report, and WG1, Chapter 12, section 12.3.1.3, and Box 21-1 in this chapter. However, due to the time lags that still exist between the generation of the climate change scenarios, and completion of the development of the related socio-economic scenarios, few of the impacts/adaptation studies assessed in WG2 actively use these scenarios. Most of the assessed literature is still based on the SRES climate and socio-economic scenarios

21.5.3.2.2. High-resolution scenarios

There have been large numbers of new simulations with regional climate models (see section 21.4.1.1), e.g., over Europe (ENSEMBLES), over North America (NARCCAP), over Asia (RMIP), over South America (CLARIS and Marengo et al. 2011), over India (HIGHNOON), and these are now being used in impacts and adaptation studies (e.g., Miles et al., 2010, Morse et al., 2009). The CORDEX program (Giorgi et al. 2009) is providing an international coordination of high resolution dynamical downscaling of the CMIP5 global models for all regions of the world. The continent of Africa has been the point of departure for the program, but as indicated in section 21.4.1.1, a number of simulations over Europe, and other continents have also already been produced.

There have also been applications of simpler downscaling techniques (e.g., the delta method, Mearns et al., 2001; and the Bias Correction Spatial Disaggregation method, BCSD, Maurer et al., 2002, 2007). The desire for higher resolution information is largely assumed to result from the needs for impacts and adaptation, but of course, particularly with regard to dynamical downscaling, the purpose is often to produce superior simulations that take into account higher resolution forcings, such as complex topography (e.g., Salathé et al., 2010) or more details in land-atmosphere feedbacks such as in West Africa (Taylor et al. 2011). Applications of some of these new higher resolution results are discussed in the section below. It must be noted that the different means of attaining high resolution climate information for use in impacts and adaptation studies have been noted for a long time (e.g., Giorgi and Mearns, 1991; Giorgi et al, 2001) but there remains many uncertainties on the relative merits of these different techniques, and particularly a paucity of information on when to use what method.

Application of high-resolution climate information

There are now a number of studies that have used dynamically downscaled information of impacts and adaptation planning. A rather complete analysis of climate impacts including possible adaptations in the Pacific North West of North America was recently conducted (Miles et al., 2010) that used both simple downscaling of the global climate model simulations from CMIP3 (Mote and Salathé, 2010) but also two different dynamically downscaled scenarios (Salathé et al., 2010). The dynamically downscaled scenarios were particularly useful for the assessment of effects

of climate change on storm water infrastructure (Rosenberg et al., 2010). Other aspects of the future aside from climate change were used in some of the sectoral analyses, such as population increase to 2025 for effects of climate on energy resources (Hamlet et al., 2010) and climate change along with air pollution scenarios for effects on human health (Jackson et al., 2010 The European PESETA program (Christensen et al. 2012) employed several RCM climate change simulations from the PRUDENCE program to investigate the impacts of climate change over Europe for agriculture, river flooding, human health, and tourism.

The ENSEMBLES project (Christensen et al., 2010) and its suite of high resolution climate projections have spawned a number of impacts studies, such as the effect of climate change on potential energy demand for heating and cooling in the Mediterranean, forest fire risk in Fennoscandia, property damage due to wind storms, crop yields and water resources in Poland, and risk of wheat yield shortfall in the Mediterranean region (Morse et al., 2009). Means of assessing risks of impacts using probabilistic information formed part of many of these projects.

The ENSEMBLES project and AMMA project (Polcher et al., 2011) developed a strong collaboration in order to provide new regional climate scenarios for use in impacts studies for West Africa. Moreover, large inter-comparison initiatives favoured the evaluation of model components relevant for impact studies, such as land-surface and chemistry models (Ruti et al., 2011).

The United Kingdom Climate Program (UKCP09) has used a combination of parameter permutation experiments (PPEs) based on the HadCM3 global climate model and multi-model ensembles (MMEs), as well as regional climate model results to develop probabilities of changes in temperature and precipitation at a 25 km resolution (Murphy et al., 2009) for all of the UK. This information is being used to determine probabilities of different impacts of climate change and possible adaptations. Results of individual regional climate model simulations are also available. A number of case studies using the UKCP09 scenarios have been developed. For example, Bell et al., (2011) used the results from 11 RCM simulations to determine potential changes in river flows throughout the UK for the A1B emissions scenario.

While the majority of articles published based on the NARCCAP suite of simulations over North America has been on climate analysis, a growing number of articles on climate impacts is appearing including impacts of climate change on available wind energy (Pryor and Barthelmie, 2011; Rasmussen et al., 2011), road safety (Hambly et al., 2012), hydrology (Burger et al., 2011; Shrestha et al., 2011), forest drought (Williams et al., 2012), and human health (Li et al., 2012).

21.5.3.2.3. Use of multiple scenario elements and focus on multiple stressors

Many more impacts and adaptation studies now use multiple scenario elements, as opposed to climate change scenarios alone. Some of the most common types of study that uses multiple scenario elements are those concerned with world hunger, where population change, land use, and economic conditions in various parts of the world make up important elements in addition to climate change (e.g., Parry et al., 2004). Arnell (2004) also used multiple aspects of the SRES scenarios in a study of global water resources, another context where population changes and future economic conditions would be critical to the study. Another type of study that commonly makes use of multiple aspects of scenarios are urban heat island and climate change studies concerned with human health (e.g., Knowlton et al., 2008; Rosenzweig et al., 2009). Recently, McCarthy et al. (2010) considered population increase up to 2050, as well as expanded urban areas to determine effects of climate change on urban heat islands. In the European Impacts Program PRESETA multiple aspects of the SRES scenarios (e.g., population and socio-economic conditions) were considered for some of the impacts areas such as human health (Watkiss and Hunt, 2012). The use of multiple scenario elements is associated with the issue of multiple stressors, which is discussed below.

One of the issues that remain somewhat unresolved is that of downscaling scenario elements. The SRES scenarios have been downscaled for Europe, for example (van Vuuren and O'Neil, 2006), but such downscaling has not been accomplished for all areas. The economic activity information in the SSP's (see above) has also been downscaled to 0.5 degree grids in some cases, but not all. This information, however, has not yet been examined carefully in the impacts and vulnerability literature (Ebi et al., submitted). (See van Vuuren et al., 2010 for a review of issues related

to downscaling of socioeconomic data). Moreover, vulnerability studies often consider other scenario elements on very local scales, and tend to use other, local sources for these scenario elements, which may or may not be consistent with the larger scale scenario elements. See the discussion of credibility of scenario elements in section 21.5.3.3.2 below.

The recognition of the importance of viewing climate change in the context of multiple stressors has increased over time. In AR4 this topic was, naturally, discussed in terms of sustainability (Chapter 20) and adaptation (Chapter 17). In the AR5 the issue of multiple stressors is incorporated into most regional and sectoral chapters, and those related to adaptation. Multiple stressors can have independent, synergistic, or antagonistic effects on particular impact areas. Typical stressors, aside from climate change, include changes in population, migration, land use, economic factors (particularly affecting adaptive capacity), technological development, social capital, air pollution, and governance structures, among others. Magrin, Marengo et al. (2011) clearly identify land-use change and shifts in major socio-economic conditions as stressors of equal importance to climate change in considering future conditions in Latin America. In the new chapter on ocean systems Portner, Karl et al. (2011) indicate the central importance of numerous changes in addition to climate (e.g., changes in nutrients), that are strongly affecting ocean ecosystem health. Hijioka, Lin et al. (2011) identify rapid urbanization, industrialization and economic development as major multiple stressors that will likely be compounded by climate change in Asia. The importance of simultaneous changes of frequency in excessive heat events and increases in air pollution have been well documented in the context of human health (Jackson et al., 2010). Human health studies in general tend to require a multiple stressor approach (Morello-Frosch, et al., 2011).

Many of the multiple stressor studies are regional or local in scope. For example Ziervogel and Taylor (2008) examined multiple stressors in South Africa, taking a survey approach. They examined two different villages in Sekhukune and found that a suite of stressors are present in the two villages, such as high unemployment, health status (e.g., increased concern about AIDs), and access to education. Concerns about climate change were only present in the context of other impacts such as availability of water. In a study on the Great Lakes region, additional stressors included land use change, population increase, and point source pollution (Danz et al., 2007). They proposed an integrated measure of multiple stresses for the region. Mawdesly et al. (2009) in considering wildlife management and biodiversity conservation note that reducing pressure from stressors other than climate change can maximize flexibility for adaptation to climate change. Stressors in this area are many, including invasion of non-native species, land-use change, and human population increases and shifts. Baker et al. (2008) note the importance of multiple stressors in the case of coral bleaching; these include sedimentation, turbidity, and nutrient loading in addition to shifts in climate. Nelson and Palmer (2007) discuss the effect of the stressors of increased watershed imperviousness, reduction in riparian vegetation, and increased siltation on water temperatures of streams, which in turn affects their suitability as a habitat. Shifts to warm-water species will result. Eakin and Wehber (2009) consider the effects of changes in demographic factors such as age structure and education level in two agricultural case studies in Latin America.

This increased focus on multiple stressors obviously increases the need for a much wider range of data and wider range of projections for the wide range of stressors, across multiple spatial scales.

21.5.3.2.4. Projections of land-use change

Land-cover and land-use are related in multiple ways to the regional distribution of vulnerabilities, both because they are intrinsically part of the distribution of natural resources and of goods and services from ecosystems (e.g. Scholes et al 2005, Janetos et al 2005), but also because they are changing rapidly as a consequence of both societal demands for those goods and services, and because of variability in the climate system. While documenting global patterns of land-cover change has been a focus for observational research for many years in particular ecosystem types (e.g. forests in Lepers et al. 2005, Hansen et al.), the projections of land-use and land-cover change have typically either focused on human-driven changes (Rindfuss 2008) or on the sensitivity of ecosystems to climate variability, but rarely both. Land-use and land-cover histories have been harmonized for use in future simulations as part of the RCP process (Hurtt et al 2011).

More recent literature begins to address new aspects of land-use and land-cover change as those processes relate to greenhouse gas mitigation actions. Meinshausen et al (in press), Van Vuuren et al. (2011), Thomson et al. (2010), and Wise et al. (2009) present scenarios of land-use and land-cover change that have focused on how those changes are also consequences of decisions about greenhouse gas mitigation, especially the potential for expansion of purpose-grown bioenergy crops. The extent and rapidity of spread of purpose-grown bioenergy crops in these studies using integrated assessment models is largely a function of economic behavior- specifically, whether a price is associated with terrestrial carbon as well as fossil fuel emissions, or whether a price is only associated with fossil fuel emissions. In some models, (Thomson et al 2010, Wise et al 2009), bioenergy crops are used for electricity generation when coupled with geological capture and sequestration. This is not a general result, however, as all integrated assessment models do not represent that particular combination of technologies. In model results that have large expansions of purpose-grown bioenergy crops, there is also a larger expansion of cropland for food production to satisfy the demand for food from growing human populations. This result is due to the fact that the competition for arable land forces agriculture onto less suitable lands and lowers their per hectare productivity. However, while the interaction between land-use, bioenergy crops, and agricultural productivity is beginning to be investigated, the interaction with the climate system itself is still largely unexplored, so our understanding of these interactions is still in a very preliminary stage. Hibbard et al (2010) present an analysis of the major uncertainties and research gaps in addressing this interaction.

21.5.3.3. Uncertainties and Credibility of Projections and Scenarios

21.5.3.3.1. Uncertainties and credibility regarding future climate

From the viewpoint of developing projections of long-term climate change, there are primarily three sources of uncertainty. This section discusses these three sources, comments on how the uncertainty has been quantified (if it has been), indicates how credible current estimates are and indicates whether we can reasonably expect reductions in these sources of uncertainty.

Future emissions and concentrations of greenhouse gases and aerosols

Future climate forcing (derived from emissions and concentrations) will be shaped primarily by: emissions of greenhouse gases, aerosols, and short-lived species into the atmosphere; and processes that control the composition of the atmosphere, such as atmospheric chemistry, terrestrial and marine components of the carbon cycle, and nitrogen cycles. Factors that influence the scale of future anthropogenic emissions include the scale of economic activity, the technologies with which human societies generate and use energy, and the public policy environment in which human activities are conducted. Hence, predicting emissions of GHG and aerosols requires being able to predict how the entire human world will develop in the future, a truly daunting task fraught with multiple profound uncertainties. This would also include determining future populations, gross domestic product (GDP), and the development of future technologies. There is not much chance of reducing these uncertainties for the long-term future. There has been an understandable reluctance to quantify the uncertainty in the emissions of greenhouse gases and aerosols, although some elements contributing to final emissions estimates have been quantified, for example, of population (also see section 21.5.3.3.2 below). Nevertheless, future emissions have mainly been presented as scenarios having equal plausibility (Parson et al., 2007). This was the case with the SRES scenarios, and is presently the case with the RCPs and SSPs (van Vuuren et al 2012, Adger et al 2011). See section 21.5.3.3.2 below for a more thorough discussion of the credibility of the elements of socio-economic scenarios.

Climate system response to forcing

Climate system uncertainty is explored through the application of global and regional climate models. While most of these models are carefully constructed to incorporate many climate-related processes and are carefully evaluated, they do not necessarily respond in the same way to a given future forcing scenario. These differences are due to scientific uncertainties about how the climate system works, differences in the way various subsystems are modeled

(e.g., land surface processes) and differences in how unresolved processes are parameterized (e.g., convection). These uncertainties are explored and characterized by analyzing the results of different types of ensembles of climate model simulations. The most common is the multi-model ensemble (MME) based on simulations with different climate models that are subjected to the same future radiative forcing. These MMEs play a central role in the analyses that contribute to the various IPCC assessments (e.g, sets of simulations from CMIP3 and CMIP5 for the AR5 Reports). There are also ensembles developed from a single climate model whose parameters are varied in systematic ways, which are referred to variously as Parameter Permutation Experiments or Perturbed Physics Ensembles (PPE) (e.g., Murphy et al., 2007).

While the climate models used to generate simulations for the AR5 are more complete than ever before (Chapter 9 WG1) (e.g., most now have fully closed carbon and nitrogen cycles, thus reducing the uncertainty regarding final concentrations in the atmosphere), there are still processes that are known to be important but are not incorporated due to incomplete understanding of the process or difficulty in modeling the process. For example, most of the CMIP5 models still do not include the explicit modeling of glacier and ice sheet dynamics (see WG 1 Chapter 9, section 9.1.3.2.8). Hence, projections of sea level rise from such models are bound to be incomplete and therefore limited. (However, better estimates are made in the AR5 using offline land ice sheet models). Other such missing processes include possible occurrence of catastrophic events such as the collapse of the Greenland Ice Sheet. Another example is that the global climate models are still limited in terms of resolution which can be important for capturing relevant processes as demonstrated in a recent study with improved vertical resolution allowing better representation of the stratosphere which then significantly influenced the projected changes in the climate over Europe (Scaife et al. 2011).

Obtaining robust predictions of climate change (i.e. at least a clear understanding of the direction of change of precipitation preferably with a level of uncertainty quantification), requires combining the projections with detailed analysis and understanding of the drivers of the changes. The most successful example of this is the application of the attribution of observed global and regional temperature changes using global models incorporating known natural and anthropogenic climate forcing factors (AR4 WG1). The global model's ability to reproduce the observed variations in temperature, the quantification of the influence of the different forcings factors and how well these influences are captured in the models provide for:

- Confidence that models capture correctly the physical processes driving the changes and thus in their ability to project future changes;
- A method of quantifying the range of sensitivities of the climate system to the different forcings factors and thus how it is likely to respond to scenarios of changes in these forcing factors.

In this situation, a robust message was derived due to having a clear understanding of the drivers of observed changes and all models reproducing these along with the direction and, to a reasonable degree of accuracy, the magnitude of the change.

Through a careful analysis of the drivers of projected changes, similar robust messages can be derived for precipitation change. Rowell and Jones (2006) performed a detailed analysis of the drivers of projected European drying in summer and concluded this signal to be robust as the dominant processes were driven by warming. In a similar analysis Kendon et al. (2010) concluded that the signal of increased daily precipitation in Europe in winter was also robust.

IPCC AR4 stated clearly that temperatures and sea-level are predicted to increase (i.e. providing quantified levels of confidence in the range in which these increases are expected to lie) and thus this information has high credibility. This is due to model simulations reproducing observed trends in these variables, an understanding of the physical drivers of these trends and that the models represent these well.

In some cases, for example precipitation on a regional scale, the sign of the change may differ from one model to another. However, it is important to note that in many cases, the difference in direction of change in precipitation simulated by, for example, two different models, indicates a lack of significant change in the precipitation compared to the natural variability in a particular region (Tebaldi et al. 2011).

Yet, it is also the case that some contrasts in direction of change are significant. In some situations, future projections may go in opposite directions to each other with neither possibility able to be excluded on the basis of our physical understanding of the drivers of these changes. For example, McSweeney et al., (2011) found that in an ensemble of GCM projections over south-east Asia, all models simulated the important monsoon processes and rainfall well but projected both positive and negative changes in monsoon precipitation and significantly different patterns of change. In this case no information on observed trends or more detailed process understanding was available but there has been little effort to analyse trends and projected changes in south-east Asia and thus the current issue of contradictory projections could be clarified with some targeted research.

Model projections may also be less consistent or inconsistent with available observations. In these cases, the projected information is less credible as explained in the following examples:

- In some cases drivers of historical change are not known so there is a lack of physically based understanding of the past to use in the assessment of confidence in the models' ability to simulate regional climate change. An example of this is the reason for the significant drying trend seen in the Sahel from the 1960s to the 1990s. Whereas statistical analysis has demonstrated the role of sea-surface temperatures (SSTs) in driving Sahel rainfall variability, and some relevant mechanisms identified, models driven by observed SSTs fail to capture the full magnitude of the drying trend (e.g. Held et al. 2005). Thus our understanding of the system and its drivers is incomplete which complicates the interpretation of future projected changes in this region (e.g. Biasutti et al., 2009, Druyan, 2010). This implies that other processes are important and thus research is required to identify these and ensure that they are correctly represented in the models. Without knowing what these processes are and thus that the models are representing all relevant processes, projections of rainfall changes over this region cannot be considered reliable.
- A more extreme case is where future projections all go in the opposite direction to the observed changes and an example of this is seen over part of the continental US which has seen cooling trends in past few decades (AR4 WG1) though the projected changes indicate a warming. This is not necessarily a contradiction though the lack of similar cooling trends in many climate models again indicates there is a process that is not being captured in the models and needs to be identified and included in the future. Then the influence of the process in projections of future climate change needs to be assessed in order to provide confidence in the sign and magnitude of any changes.

In these cases where future projections differ significantly or go in opposite directions, it is still important to provide information on the range of changes. The likelihood that temperatures (and sea-level) will continue to rise in the future is sufficient to motivate a response to these predicted changes and, in general, information on other climate variables will also be required. Thus it is important to be able to characterize the range of plausible changes in these other variables.

One approach is to use a Bayesian probabilistic framework to combine the range of information that may include differences in direction of change in precipitation in a global climate model (e.g. Tebaldi and Knutti, 2007, Harriss et al., 2012) or in a global model and then a regional model driven by the global model (e.g., Déqué and Somot (2010). Another is to identify a subset of available models whose response characterises the range of projected futures (e.g. McSweeney et al., 2011).

It is expected that with model improvements (e.g., including more important processes and modeling processes more completely) that the uncertainty due to climate (model) response will be reduced over time in certain ways. However, this does not necessarily mean that all metrics of uncertainty will be reduced at once. It is quite possible that improving the representation of processes will not immediately result in reduction of uncertainties regarding the likely range of temperature change in central Kansas in 2050, for example (Mearns, 2010). One of the FAQs presented in Chapter 1 of WG1 discusses this issue in more detail.

Internal variability

Long-term projections of climate change are subject to uncertainty resulting from the internal variability of the climate system. The relative role of this type of uncertainty compared to the other sources of uncertainty (climate

model response uncertainty and forcing uncertainty), are a function of the future time horizon being considered and the spatial scale of analysis (Hawkins and Sutton, 2009; 2011). Here we use the term natural or internal variability to refer to unforced variability internal to the climate system. Hence this definition does not include variability related to the occurrence of natural phenomenon, such as volcanoes. Internal variability is usually explored by running sets of climate model simulations (ensembles) using different initial conditions for each simulation. Traditionally the number of ensemble members has not been large (e.g., around 3 in the CMIP3 data set), but the number has increased in the CMIP5 set of simulations to about 7. However, some recent research has explored larger numbers of ensemble members (e.g., Deser et al., 2010) and has thus come up with improved measures of natural variability. In this case 40 different members were produced, which represent how much the climate can vary based on random internal variations. The variations across ensemble members can be considerable on various spatial scales, and there is considerable evidence that this kind of uncertainty may not be particularly reducible (Deser et al. 2012). The issue of internal variability is more thoroughly discussed in WG1 Chapter 12, section 12.1.1.2.

21.5.3.3.2. Credibility and uncertainties regarding socioeconomic scenario elements

Credibility

The fact that scenarios serve both as tools of investigation for the scientific community and as the basis of information on possible futures for decision-makers introduces additional demands for the credibility of scenarios beyond that typically required of other scientific studies (van Ruijven et al. forthcoming).

Cash et al. (2003) distinguish three criteria for effectively linking scientific knowledge to policy action: credibility, salience, and legitimacy. Credibility refers to the scientific adequacy of a policy-relevant study. Salience refers to the relevance of a study's findings to the needs of decision-makers, while legitimacy refers to the perception that the study was produced in a manner that is respectful of divergent values and beliefs. Cash et al. (2003) find these attributes to be tightly coupled and suggest that efforts to enhance one criterion normally introduce tradeoffs for the others. Studies examining the performance of scenarios in climate change research across all three of these criteria are rare, but a general conclusion has been that most effort has been expended on credibility with much less attention to salience and legitimacy (Hulme and Dessai 2008, Garb et al. 2008, Girod et al. 2009).

Perhaps partially in recognition of the limitations that scenarios have had historically with salience and legitimacy, new scenarios for future climate change research will have a dramatically new structure. Under the parallel process (Moss et al. 2010), research streams that developed independently around climate scenarios (inspired by representative concentration pathways, or RCPs; see van Vuuren et al. 2011) and socioeconomic scenarios (shared socioeconomic pathways, or SSPs; see O'Neill at al. forthcoming) will be brought together to enable integrated analyses of mitigation, adaptation, and residual impacts. (See Box 21-1 for an overview of the new scenarios). RCPs aim to be the concept that coheres climate and socioeconomic elements together for reference scenarios (i.e. alternative futures assuming no new climate policy; see Ebi et al. forthcoming and van Vuuren et al. forthcoming). In principle, such coherence is possible, as RCPs can serve as both inputs to climate modeling and as target outputs to IA modeling. Additionally, one of the main conclusions of the SRES (Nakicenovic et al. 2000) supports this aspect of the new scenario design, as fairly different socioeconomic conditions could give rise to similar emissions trajectories. Subsequent studies have arrived at similar results (van Vuuren et al. 2008).

However, heeding the warning of tradeoffs from Cash et al. (2003), it remains to be seen if enhancements to scenario salience may result in diminished scientific credibility. It is unclear how difficult it will be to bring independently developed climate and socioeconomic scenarios together in an internally consistent manner during the integration phase (O'Neill and Schweizer 2011). Additionally, the SSP framework (O'Neill et al., forthcoming) introduces another layer of complexity by labeling SSPs describing globally aggregated trends as "basic" versions, while more elaborate SSPs, which will be geared toward sector-specific or more regional and localized analyses, will contain additional socioeconomic detail and are called "extended" SSPs. The possibility that additional details in extended versions of the SSPs could upset the internal consistency of the basic SSPs cannot be dismissed, and such problems will only be uncovered as the SSPs are further developed and used.

In this regard, recent scholarship has suggested that the exclusion of some socioeconomic details in socioeconomic scenario studies can affect the internal consistency, and therefore the credibility, of a study overall. This is due to the common practice of Story and Simulation (SAS; Alcamo 2008) for scenarios, where narrative descriptions of alternative futures serve as the inspiration for socioeconomic simulations. At the initial stage of story development, the first internal consistency test is that these stories be plausible. Thereafter, integrated assessment (IA) models attempt to replicate qualities of these stories. The ability of the IA model to simulate the story is viewed as a more rigorous test for internal consistency. Conventional wisdom is that so long as IA models are able to simulate the conditions described in the story, the story (and hence its assumed combinations of socioeconomic elements) has been demonstrated as internally consistent and therefore credible. Thus, a strength of SAS is that it marries the malleability of stories to the rigors of simulation (Raskin et al. 2005). As noted in the AR4, stories in SAS can offer a point of entry for multi-scalar scenario analyses (Lebel et al., 2005; Kämäri et al., 2006). Despite these benefits, some scholars have pointed out a potentially serious deficiency in the practice of SAS, as stories often include details that make them plausible which IA models do not include (Kok 2009, Schweizer and Kriegler 2012, Schweizer and O'Neill forthcoming). The exclusion of some details in IA models may affect the determination of whether a story is plausible (Lloyd and Schweizer, forthcoming) let alone internally consistent. For example, one of the findings of Schweizer and Kriegler (2012), who employed a systematic method for assessing the internal consistency of the qualitative aspects of scenarios, is that assumptions regarding social priorities (e.g. contrasting hypothetical worlds that are economically versus environmentally focused) can make the difference between marginal and strong internal consistency for SRES scenarios with the lowest emissions profiles.

Along with the new research opportunities that will be made possible under the new scenario process, the scientific community must also revisit what credibility means across extended SSPs, basic SSPs, and SSP+RCP scenario combinations. Scholarship on environmental scenario exercises crossing geographical scales suggests that linkages between scenarios at different scales can be hard or soft (Zurek and Heinrichs 2007), where downscaling would be an example of a hard linkage while other similarities between scenarios would be soft linkages. In the context of the new scenario framework, some thought has been given to the circumstances under which strong internal consistency should be retained (e.g. global SSP+RCP scenarios) and when it may be relaxed (e.g. the internal consistency of a provincial vulnerability assessment, based on extended SSPs + regional RCP climate projections, with global SSP+RCP scenarios) (van Vuuren et al. 2012). Nevertheless, how to apply flexible interpretations of scientific adequacy and maintain scenario credibility is relatively uncharted territory for scenario-based environmental change assessments. There will be a need for studies to document best practices in this respect and for the scientific and policy communities to move toward consensus.

In conclusion, we find that few studies have assessed the performance of scenarios and their reception by decision-makers, whether focusing on credibility (e.g. internal consistency) or also considering salience and legitimacy. The new scenario process will also introduce new complexities for scenarios, and attention should be paid to what these complexities may mean for scenario credibility.

Quantifications of uncertainties of scenario elements and scenarios

Since AR4, little has changed over the controversy for whether probability density functions (pdfs) should be assigned to emissions pathways or other socioeconomic scenario elements (e.g. population growth, income growth) (Parson et al., 2007). Where studies have incorporated probabilities, they have done so in a variety of ways. Some propose or have demonstrated probabilistic estimates for socioeconomic scenario elements. A study by van Vuuren et al. (2008) applied conditional probabilistic estimates for socioeconomic scenario elements that would be consistent with alternative SRES storylines. Van Vuuren et al. (2008) were careful to comment that the purpose of such conditional probabilities is not to evaluate the likelihood of the underlying storylines but to explore other topics such as the ranges of emissions for different storylines. In contrast, Morgan and Keith (2008) have proposed that likelihoods for scenarios could be obtained through a subjectivist approach, where probabilities are obtained from experts. In this vein, some expert elicitation studies regarding technological change (Curtright et al. 2008, Anadon et al. 2011), including those combined with economic modeling (Böhringer et al. 2009, Baker et al. 2009), have further demonstrated that experts could assign subjective probability judgments to alternative future outcomes. Other examples of uncertainty quantification include probability estimates for the feasibility of achieving temperature or

concentration targets (Keppo et al. 2007, O'Neill et al. 2009). In these latter cases, socioeconomic elements in emissions scenarios are not treated probabilistically; instead, assumptions about climate sensitivity or perfect foresight are adjusted, and an IA model is run multiple times. The frequency of the model runs in the ensemble that achieve the temperature or concentration targets provide probabilistic estimates for achieving the policy targets.

Because there are multiple ways to quantify uncertainties in scenarios, the new parallel design for socioeconomic and climate scenarios may or may not pose challenges for further uncertainty quantification. Although decoupled socioeconomic and climate scenarios may make it difficult to determine probabilities for climate scenarios based on a probabilistic analysis of socioeconomic scenarios alone, other opportunities for probabilistic analyses will be retained. For example, it would be possible to do conditional probabilistic studies with socioeconomic scenarios independently and determine probabilistic ranges for emissions. If subjective probabilities for socioeconomic scenario elements were also introduced, it would be possible to conclude conditions under which particular emissions scenarios would be expected to be more likely. In the latter case, likelihood judgments for emissions scenarios may be translatable to likelihood judgments for RCPs, and therefore, related climate projections.

21.6. Knowledge Gaps and Research Needs

The issues of the regional context of climate change are arguably the thematic area most in need of attention to advance adaptation response, policy, and decision making. The needs range from the practical questions requiring applied research, to more fundamental theoretical questions. Table 21.4 identifies leading foci that currently constrain the adaptation community, and where a solid advance of knowledge advance would contribute to substantial value for the broad adaptation community.

[INSERT TABLE 21-7 HERE
Table 21-7: Leading knowledge gaps and related research needs.]

Frequently Asked Questions

FAQ 21.1: Should we be concerned about impacts of climate change in other parts of the world?

Short answer: Regional impacts of climate change, both adverse and beneficial, may have ramifications in other parts of the world. Different types of impacts can be of importance to a variety of interest groups. Cross-regional concerns about four types of impacts can be distinguished: 1) Concerns about large-scale geophysical impacts, 2) Concerns about socio-economic and geopolitical impacts, 3) Concerns about social instability due to rapid-onset events, and 4) Concerns internationally about impacts occurring locally. Some illustrations of these are provided below, along with the types of groups who might show interest.

Long answer: Climate change is a global phenomenon, but the expression of that change and its impacts on natural systems and society varies enormously from place to place and over different time scales. Some impacts may be gradual responses to long-term trends, sometimes referred to as "slow-onset" impacts. More prominent, though also more difficult to attribute to a changing climate, are "rapid-onset" impacts of extreme weather events[1] such as droughts, floods or storms. In both cases, regional climate change has direct impacts on systems and communities that are exposed to that change in the same region. However, such impacts can also have implications much farther afield, sometimes in completely different parts of the world. The reasons for this relate to key regional interdependencies that are present both in the global physical climate system as well as in economic, social and political systems that are themselves becoming increasingly globalised. Cross-regional concerns about four types of impacts can be distinguished:

1) *Concerns about large-scale geophysical impacts*. Some types of geophysical impact can have large-scale repercussions well beyond the regions in which they occur. A well-known example of this is the melting of land-based ice, which is contributing to sea-level rise (and adding to the effects of thermal expansion of the oceans), with implications for low-lying areas far beyond the polar and mountain regions where the melting is taking place. These impacts are ongoing and are projected to take centuries or millennia to slow down or

halt, which would require that climate change stabilisation be achieved first. The types of actors with an interest in these impacts include policy-makers involved in discussions about reducing global greenhouse gas emissions in order to stabilise the climate, decision-makers needing to formulate strategies for coastal management and flood protection under rising sea levels, or insurers offering coverage for flooding, erosion and related risks.

2) *Concerns about socio-economic and geopolitical impacts*. Local, slow-onset impacts of climate change may also trigger higher-order responses that have wider social, economic and geopolitical implications. For example, there has been much debate in recent years on the question of environmental refugees, where the argument has been put forward that climate change is degrading environments in some regions to such an extent that the livelihoods of local populations have or will become unsustainable, and they are forced to migrate to other regions. While there is evidence of international migration in the wake of extreme events such as hurricanes (e.g. population displacement from central America to the United States following Hurricane Mitch in 1998), the evidence for longer-term climatic causes of migration is disputed, and is also confounded by the growing phenomenon of economic migration. Nonetheless, geopolitically this is an issue of increasing importance to national and international policy makers.

   A second example of a regional impact of climate change with socio-economic and security implications is the accelerated shrinkage of Arctic sea ice that has been observed in recent years. This is projected to continue into the future under sustained regional warming, opening Arctic shipping routes as well as providing access to valuable mineral resources in the exclusive economic zones of countries bordering the Arctic. For example, under some scenarios, it is estimated that moderately ice-strengthened ships could have almost complete summer access to Arctic routes such as the Northwest Passage, Northern Sea Route and Trans-Polar Route by the end of the 21st century, representing significant savings for trans-continental shipping currently using routes via the Panama and Suez Canals. On the other hand, there are also numerous risks that would accompany such commercial exploitation, including shipping accidents, pollution, threats to livelihoods among indigenous communities, and general degradation of an already fragile environment. National governments, representatives of indigenous peoples, international freight carriers, resource extraction industries and environmental agencies are among the parties having a stake in these future developments.

3) *Concerns about social instability due to rapid-onset events*. A third class of local impacts with global ramifications, are those that are caused by rapid-onset, extreme weather events, which may curtail production of some key commodities that are traded internationally, leading to shortages of supply and hence increased prices to consumers. For instance, there are recent examples of price spikes in some basic food commodities that caused local unrest among consumers in some parts of the developing world. Though these price rises were triggered by weather-related crop failures in exporting regions, the underlying causes of reduced food supply are more complex, and include reallocation of food crops by some major exporters for use as biofuels, national trade protection policies, as well as market speculation. Some key actors with an interest in such events might include bodies regulating international commodities trading, national governments, regional trading blocs, public law and order authorities, and aid agencies.

4) *Concerns internationally about impacts occurring locally*. Some impacts are local and may have little or no immediate effect outside the regions in which they occur. Nonetheless, they may be of concern to actors outside that region for a range of reasons, including: (i) disaster relief (e.g., to ameliorate the impacts of malnutrition or disease brought on by weather-related events), (ii) environmental protection (e.g., conservation of locally threatened and valued species), (iii) enhancing adaptive capacity (e.g. through capacity building and other development projects that enhance resilience to climate change), or (iv) exploiting potential opportunities (e.g. through foreign investment in agricultural production in regions where future climate change impacts may be beneficial for productivity). Here, some key actors who might wish to consider such impacts include national and international development agencies, humanitarian organisations, multi-national corporations, and environmental organisations.

[FOOTNOTE 1: Although extreme weather events on their own can be very difficult to attribute to anthropogenic climate change, long-term trends in such events are projected by climate models (Cross reference?), and in some cases are already being observed (see FAQ 2.2, Chapter 2, WG I).]

FAQ 21.2: Is the highest resolution projection the best to use? [placeholder draft]

Short answer: *A common perception is that higher resolution equates to more information. Unfortunately data does not equal information, and more high resolution data does not necessarily equal more information. Hence, while there are many methods that can increase resolution, it is not a given that there will be more skill in the final product. For example, simple approaches such as interpolation or perturbing observed data fields with GCM information increase the resolution but add no high resolution climate change information. Using downscaling methods will add a high resolution component but there will be an extra error associated with the additional method applied which needs to be considered. More importantly, if downscaling is applied to only one or two GCMs then the resulting high resolution scenarios are unlikely to span the full range of projected changes that a large GCM ensemble would indicate are plausible futures. Thus for many applications, such as understanding the full envelope of possible impacts resulting from our current best estimates of plausible change in a regional climate system, lower resolution data can be more informative. At the end of the day, no one data set is best, and it is through the integration of multiple sources of information that robust understanding of change is developed.*

Long answer: placeholder pending a support graphic/cartoon being developed

FAQ 21.3: Are earlier assessments still valid? [placeholder draft]

Short answer: [to be drafted]

Long answer: The IPCC has conducted four major Assessments, starting in 1990, and each has included the equivalent of a Working Group 2 Report. The current report represents the fifth assessment. The reports through time have increased in length, scope, and complexity. But the essential goal of the reports has a core commonality. In the first report, it is stated that the 'responsibility of Working Group II is to describe the environmental and socioeconomic implications of possible climate changes over the next decades caused by increasing concentrations of greenhouse gases' (IPCC 1990). By the Third and Fourth Assessments, the WG2 Assessments had expanded to explicitly consider vulnerability and adaptation, in addition to impacts. In the second report both mitigation and adaptation were considered in WG2, but the sections on adaptation were very basic. So we see that the organization of the Working Groups, including their remits, has changed over time. But our concern in this FAQ is whether the content of the earlier reports are still valid, not whether the structure of the reports has significantly changed. Within the Second Report (SAR) concerns regarding vulnerability and adaptation were already present, as were many concepts that received more intensive coverage in the later reports, such as multiple stressors, adaptive capacity, and vulnerability. But the earlier reports (IPCC 1990, 1995) tended to be much less quantitative than later reports, and provided less detail on a regional scale. Yet many of the concerns expressed in later reports (2001, 2007, 2014) are already adumbrated in the earlier ones (e.g., negative impacts on human health from increased heat waves, decreased water resources and strains on cropping systems, changes in ecosystem composition). By the 2001 Report, much more detailed regional analysis was taken on, and the structure of a sectoral section and a regional section came into being, along with a detailed chapter on adaptation. Also greater attention was placed on how uncertainties are expressed and quantified. By the 2007 report, the major new theme of assessment of observed changes and responses in natural and managed systems became a subject of its own, although it was introduced in the Third Assessment Report (TAR). Also by the time of the TAR, greater emphasis was placed on the concept of sustainability as a broader framework through which climate change impacts should be viewed.

[Placeholder for figure of different IPCC assessments, and the new elements that emerged with each report]

The overall message of this FAQ would be that yes, in a general sense, the earlier assessments are still valid, but the assessments have become much more complete over time, evolving from making very simple, general statements about sectoral impacts, through greater concern with regions regarding impacts and vulnerabilities, through to greater emphasis on sustainability, equity, and deeper examination of adaptation options. Finally in the current report (IPCC 2014) we see four chapter on adaptation, and a much more explicit treatment of the challenges of decision-making. The progression of the reports reflects tremendous scientific progress and deep learning from one report to the next. Obviously one can learn the most about impacts, vulnerability, and adaptation in the context of climate change by looking at the most recent report. It is certainly much more complex and complete in its

treatment of defining societies challenges in the face of climate change, possible adaptation, and how to maintain a sustainable world even with the challenges of climate change. So, the earlier reports are for the most part valid, but they appear incomplete and somewhat naïve compared to our most recent efforts. Observing the progress represented by each new report is a validating experience in and of itself.

FAQ 21.4: What information should I take into account for climate risk management for the 20-year time horizon?

Short answer: For climate-affected decisions that play out over the coming 20 years, it is important to be aware that the climate is changing. Climate trends over the recent past may provide guidance on what is expected in the near future if the reasons for these trends are known and are expected to intensify. Also, any climate model projections in which there is confidence for climate variables of importance are potentially useful. However, climate trends and model projections will at most provide only some relevant information for managing risk for the 20-year time horizon. To effectively manage these risks, it is important to (i) properly characterize the decision-making context, including trends in vulnerability and exposure to climate and weather phenomena (ii) understand the natural variability in the key climate variables as well as any robust predictions of changes; (iii) where relevant, make use of forecasting on shorter timescales if early-warning systems are or could be important in managing the risks involved.

Long answer: How to manage risks for decisions with a 20-year time horizon clearly depends on the specific decision-making context. It is essential to first characterize the vulnerability to climate conditions of the issue being addressed, and to determine how climate conditions interact with other factors, which may be changing more rapidly than the climate itself. For example, if the issue is design of contingency plans for disasters in a rapidly growing city, vulnerability will depend on the people and assets at risk in a particular location, including the types of buildings and land use. If the issue is agriculture investments (say, a switch of crops), vulnerability will also depend, for instance, on market conditions, the availability of credit and insurance.

A second element that clearly depends on a good understanding of the decision-making context, is to assess which climate variables matter most. If the issue is design of contingency plans for disasters, it is clearly the extremes that matter most; in the case of agriculture it may be average seasonal rainfall, but also seasonal onset, or maximum daily rainfall.

Thirdly, once that decision-making context, and the climate variables that matter most to the risks being addressed, are clear, it is important to recognize that the climate of today, and of the next 20 years, is already different from the past climate. Basic statistics based on historical records may not provide the best guess for the climate will look like in the next 20 years.

On the other hand, on their own, the changes in climate conditions as projected by climate models for the period between now and the middle or even the end of the century, may not provide the best guidance, either. Taken over just 20 years, the long-term trends are often relatively small compared to the natural variability in the climate system. And while so-called decadal predictions, based on climate models that are initialized using current climate system observations, are improving, their skill is still low.

In simple terms, for many decisions to be taken with a 20-year time horizon, climate change primarily means that uncertainty about the precise conditions to expect is increasing. For some variables, such as average temperature, the trends may be pretty clear: there is a higher chance of higher average temperatures, and of high temperature extremes. For others, such as rainfall and particularly rainfall extremes for instance, the uncertainty is much higher.

So what climate information can be used to manage risks under these circumstances?

First of all, it is essential to properly characterize historical climate variability: how has the climate varied in the past (including extremes, and looking at seasonal, annual and decadal variability). Assessing possible risk management options for robustness under that range of conditions is often a very important first step (and most often much more important than simply focusing on the projected trend due to climate change).

Secondly, for many climate variables, forecasting on shorter timescales, such as regular weather forecasts, and in some regions seasonal forecasts, may provide good indications of what to expect in the relatively near term, which also helps manage some of these risks, including the rising uncertainties.

Thirdly, it is important to be aware of observed trends to get a sense of how the climate may already have been changing. This can be a challenge, somewhat depending on the climate variables of interest, and particularly in regions with more limited data, in terms of coverage and timespan. For instance, if only a 20 years of observational data is available, it will not be possible to confidently interpret, let alone extrapolate a trend.

For some climate variables, climate models may provide additional guidance on how things may already have changed, and what to expect for the coming 20 years. Rather than interpreting these results as a prediction of the precise conditions that will happen, they are often best used as a guide for the direction of change, and thus of the wider envelope of conditions that should be taken into account when making decisions that will be more robust in the conditions to expect in the coming 20 years.

In order to assess the confidence that should be attached to these model projections, it is often important to cross-compare different models, and to know how well these models have performed in simulating the same variables in the same region in the past. This often requires expert judgment. Regional assessments of observed and projected changes in some key climate variables, such as summarized in IPCC reports [include specific chapter references], may provide a rough indication of the direction of change, or the uncertainties, that should be taken into account to aim for more robust decisions in a changing climate.

Finally, decisions with an apparent 20-year time horizon may actually have long-term consequences. For instance, as an investment decision to build a coastal tourist resort with an economic lifetime of 20-years, may actually have severe long-term implications, in this example by changing ecosystems and coastal morphology, but also by triggering different settlement patterns and infrastructure in the surrounding areas. It is becoming increasingly important to take account of such longer-term dimensions of risk in shorter-term decisions, and avoid maladaptation.

FAQ 21.5: How do I find out how vulnerable my region is (am I a hot spot)?

PLACEHOLDER

Cross-Chapter Box

Box CC-RC. Regional Climate Summary Figures

[Noah S. Diffenbaugh (USA), Daithi Stone (Canada), Filippo Giorgi (Italy), Bruce Hewitson (South Africa), Richard Jones (UK), Geert Jan van Oldenborg (Netherlands)]

The WGII regional climate summary figures draw on climate model simulations archived in Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). The CMIP5 simulations are also the basis for the figures presented in Annex I of the WGI contribution (*Atlas of Global and Regional Climate Projections*). The CMIP5 archive includes output from approximately three dozen climate models, including atmosphere-ocean general circulation models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, varies between the different CMIP5 experiments.

In contrast to CMIP3 (which used the IPCC SRES scenarios), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011) to simulate the climate response to possible changes in forcing over the 21st century. The WGI Atlas focuses on RCP4.5, with supplemental analysis of RCP2.6, RCP6.0, and RCP8.5. The WGII regional climate figures compare RCP4.5 and RCP8.5, using the same baseline, mid-21st-century, and late-21st-century time periods as the WGI Atlas (1986-2005, 2046-2065, 2081-2100). The RCPs exhibit overlapping likelihood of global warming in the mid-21st-century period (including median warming of 1.4˚C and 2.1˚C above the late-20th-century baseline in RCP4.5 and RCP8.5, respectively) (Rogelj et al. 2012), but divergent likelihood of global warming in the late-21st-century period (including median warming of 1.8˚C and 3.8˚C above the late-20st-century baseline in RCP4.5 and RCP8.5, respectively) (Rogelj et al. 2012). Given that real emissions have tracked on or above RCP8.5 in recent years (Peters et al. 2013), the regional climate figures are focused on the middle (RCP4.5) and upper end (RCP8.5) of the range of RCPs available in CMIP5.

The regional climate figures show the mean annual temperature and precipitation, categorizing differences in the CMIP5 simulation of the baseline and future periods into four classes. The classes are constructed based on the IPCC uncertainty guidance, which provides a quantitative basis for assigning likelihood statements (Mastrandrea et al. 2011). The classifications in the figures are constructed to parallel the 66-100% ("likely") and 90-100% ("very likely") probability ranges identified in the IPCC uncertainty guidance.

However, there are a number of plausible assignments of likelihood in a multi-model ensemble (e.g., (Knutti et al. 2010)). The classifications in the regional climate figures are based on two interpretations of likelihood reflected in the literature. The first interpretation is the likelihood that the climate in the future period is different than the climate in the baseline period (e.g., (Tebaldi et al. 2011). The regional climate figures use the percentage of models for which the simulated change exceeds two standard deviations of the simulated baseline variability as the measure of probability that the simulated future climate is statistically different than the simulated baseline climate. The second interpretation is the likelihood of the sign of change (e.g., (Christensen et al. 2007; Field et al. 2012). The regional climate figures use the percentage of models that exhibit the same sign of change as the measure of probability of increase or decrease in a given quantity.

The four classifications depicted in the regional climate figures are:

1) White indicates areas where less than 66% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability.
2) Gray indicates areas where greater than 66% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability, and less than 66% of the models agree on the sign of difference.
3) Colors with circles indicate areas where greater than 66% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability, and greater than 66% of the models agree on the sign of the difference. The color contour shows the magnitude of the multi-model mean difference between the future and baseline periods.
4) Colors without circles indicate areas where greater than 90% of the models exhibit difference between the future and baseline periods that exceeds twice the baseline variability, and greater than 90% of the models agree on the sign of the difference. The color contour shows the magnitude of the multi-model mean difference between the future and baseline periods.

Only those models that have archived output from the historical, RCP4.5 and RCP8.5 experiments are included. For each of the included models, all realizations are used. For a given model, the mean and variability of each realization is first calculated for each period. The mean of the individual-realization mean and variability values are then calculated across the realizations of that model in each period, yielding model-mean mean and variability values derived from the timeseries of each realization (rather than from the mean of the timeseries). The difference between the model-mean in the future and baseline periods is then calculated for each model, and compared with each model's model-mean baseline variability. (Prior to analysis, each realization of each model is first interpolated to a common 1˚ geographical grid using linear interpolation.)

Because the regional climate figures quantify differences between 20-year periods, the measure of baseline variability is chosen to reflect the variability between 20-year periods in the baseline climate forcing. Given that the baseline period is selected as 1986-2005, the baseline variability is calculated as the standard deviation between the 20 20-year periods ending in the years 1986 through 2005 (1967-1986, 1968-1987, … , 1986-2005). Although the 20 20-year periods are not independent, they reflect the population of 20-year periods within the recent climate forcing regime, and a 20-year period that is more than two standard deviations removed is considered to be reflective of a different climate.

In addition to maps of the CMIP5 simulations, the regional climate figures also include maps of observed temperature and precipitation differences between the baseline period (1986-2005) and the early 20th century (1906-1925). The observational analyses use the CRU TS3.10.01 gridded station-based temperature and precipitation data (CRU 2012). On the observational panel, white indicates areas where the difference between the baseline and early-20th-century periods does not exceed two standard deviations of the early-20th-century variability. Colors indicate areas where the difference between the baseline and early-20th-century periods exceeds two standard deviations of

the early-20th-century variability, with the color contours showing the magnitude of the difference. For the observational analyses, the early-20th-century variability is calculated as the standard deviation between the 20 20-year periods beginning in the years 1906 through 1925 (1906-1925, 1907-1926, … , 1925-1944).

[INSERT FIGURE RC-1 HERE
Figure RC-1: Change in annual temperature. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

[INSERT FIGURE RC-2 HERE
Figure RC-2: Change in annual precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

CC-RC References

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Table 21-1: Dimensions of the institutions and actors involved in climate change decision-making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decison-making domains are illustrative. Modified and extended from Mickwitz (2009).

Level: \ Domain:	Economy	Energy	Food/fibre	Technology	Environment	...
	Coherent policies and decision-making					
Global	IMF/WB WTO MDGs NGOs	IEA NGOs	FAO WTO CLOS (fisheries) NGOs	WIPO NGOs	UNFCCC CBD Montreal Protocol NGOs	
Trans-national	MDBs MFIs OECD/EU CLOS (transport)	OPEC Electric grid operators Oil/gas distributors	AFTA COMESA MERCOSUR EU CAP/CFP	Multi-nationals R&D EU Innovation Union	CLRTAP MRC LVBC EU Directives	
National	Ministry/Gov. Dept./Agency Banks Taxation	Ministry/Gov. Dept./Agency Energy provider Energy regulator	Ministry/Gov. Dept./Agency Tariffs, Quotas, Regulations	Ministry/Gov. Dept./Agency Education/R&D/ Innovation	Ministry/Gov. Dept./Agency Environmental law	
Sub-national	State/Province/ County/City Taxation	State/Province/ County/City Public/private energy provider	State/Province/ County/City Extension service Land use planning	State/Province/ County/City Incentives Science parks	State/Province/ County/City Protected areas Regional offices	
Local	Micro-finance, Co-operative, Employer, Voter, Consumer	Renewables Producer, Voter, Consumer	Farmer, Forester, Fisher, Landowner, Voter, Consumer	Entrepreneur, Invester, Voter, Consumer	Environmentalist, Landowner, Voter, Consumer	

Multi-level organisation and governance

Integrated decision-making and governance

Acronyms: IMF – International Monetary Fund; WB – World Bank; WTO – World Trade Organization; MDGs – Millennium Development Goals, NGO – Non-governmental Organization; MDBs – Multilateral Development Banks; MFIs Multilateral Financial Institutions; OECD – Organisation for Economic Co-operation and Development; EU – European Union; CLOS – United Nations Convention on the Law of the Sea; IEA – International Energy Agency; OPEC – Organization of the Petroleum Exporting Countries; FAO – Food and Agriculture Organization of the United Nations; AFTA – Association of Southeast Asian Nations (ASEAN) Free Trade Area; COMESA – Common Market for Eastern and Southern Africa; MERCOSUR – Mercado Común del Sur (Southern Common Market); CAP/CFP – Common Agricultural Policy/Common Fisheries Policy; WIPO – World Intellectual Property Organization, UNFCCC – United Nations Framework Convention on Climate Change; CBD – Convention on Biological Diversity; CLRTAP – Convention on Long-range Transboundary Air Pollution (Europe, N. America, C. Asia); MRC – Mekong River Commission For Sustainable Development; Lake Victoria Basin Commission

Table 21-2: Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SR). Major assessments are subdivided by the three Working Group reports, each described by generic titles.

IPCC report [references]	**Year**	**Treatment of regions**
First Assessment Report (FAR) [1, 2, 3]	1990	*Climate*: Climate projections for 2030 in 5 sub-continental regions; Observations averaged for northern/southern hemisphere, by selected regions and by 20° latitude x 60° longitude grid boxes
		Impacts: Agriculture by continent (7 regions); Ecosystem impacts for 4 biomes; water resources for case study regions; Oceans and Coastal Zones treated separately
		Responses: Emissions scenarios by 5 economic groupings; Energy and Industry by 9 regions; Coastal Zone and Wetlands by 20 world regions
Supplements to FAR [4, 5]	1992	*Climate*: IS92 emissions scenarios by 7 world regions
		Impacts: Agriculture by continent (6 regions); Ocean Ecology by 3 latitude zones; Questionnaire to governments on current activities on impacts by 6 WMO regions
***SR**: Climate Change 1994* [6]	1994	Evaluation of IS92 emissions scenarios by 4 world regions: OECD, USSR/E. Europe, China/Centrally Planned Asia and Other.
Second Assessment Report (SAR) [7, 8, 9]	1995	*Climate*: Gridded proportional circle maps for observed climate trends (5° latitude/ longitude); climate projections for 7 sub-continental regions
		Impacts, Adaptations, Mitigation: Energy production statistics by 10 world regions; Forests, Wood Production and Management by three zones: Tropical, Temperate, Boreal; separate chapters by physiographic types: Deserts, Mountain Regions, Wetlands, Cryosphere, Oceans, and Coastal Zones and small islands; country case studies, Agriculture by 8 continental-scale regions; Energy supply by 8 world regions
		Economic and Social Dimensions: Social Costs and Response Options by 6 economic regions
***SR**: Regional Impacts* [10]	1998	10 continental-scale regions: Africa, Arctic and Antarctic, Australasia, Europe, Latin America, Middle East and Arid Asia, North America, Small Island States, Temperate Asia, Tropical Asia. Subdivisions applied in some regions; Vegetation shifts mapped by 9 biomes; Baseline (1990) Socio-Economic data provided by country and for all regions except polar.
***SR**: Land-Use Change and Forestry* [11]	1998	9 Biomes; 15 land-use categories; National and Regional case studies.
***SR**: Aviation* [12]	1999	Observed and projected emissions by 22 regional air routes; Inventories by 5 economic regions
***SR**: Technology Transfer* [13]	2000	Country case studies; Indicators of technology transfer by 6-7 economic regions
***SR**: Emissions Scenarios* [14]	2000	4 SRES world regions defined in common across integrated assessment models; 11 sub-regions; Driving Factors by 6 continental regions
Third Assessment Report (TAR) [15, 16, 17]	2001	*Climate*: gridded observations of Climate trends; 20 example Glaciers; 9 Biomes for Carbon Cycle; Circulation Regimes for model evaluation; 23 "Giorgi" regions for regional climate projections
		Impacts, adaptation and vulnerability: Example projections from 32 "modified-Giorgi" regions; Basins by continent; 5 Coastal types; Urban/Rural Settlements; Insurance by economic regions; 8 continental-scale regions equivalent to 1998 Special report but with single chapter for Asia; Subdivisions used for each region (Africa, Asia and Latin America by climate zones; North America by 6 core regions and 3 border regions)
		Mitigation: Country examples; Developed (Annex I) and Developing (non-Annex I); Various economic regions; Policies, Measures and Instruments by 4 blocs: OECD, Economies in Transition, China and Centrally Planned Asia, and Rest of the World.
***SR**: Ozone Layer* [18]	2005	Various economic regions/countries depending on sources and uses of chemicals;
***SR**: Carbon Capture and Storage* [19]	2005	CO_2 sources by 9 economic regions; potential storage facilities: by geological formation, by oil/gas wells, by ocean depth,; costs, by 4 economic groupings

Fourth Assessment Report (AR4) [20, 21, 22]	2007	*Climate*: Land-use types for surface forcing of climate; Observations by 19 "Giorgi" regions; Modes of variability for Model Evaluation; Attribution of climate change by 22 "Giorgi-type" regions and by 6 ocean regions; Climate statistics for 30 "Giorgi-type" regions; PDFs of projections for 26 regions; summary graphs for 8 continental regions
		Impacts, adaptation and vulnerability: Studies reporting observed impacts by 7 IPCC regions; comparison of TAR and AR4 climate projections for 32 Giorgi regions; Ecosystems by 11 biomes; Agriculture by latitudinal zone; Examples of Coastal mega-Deltas; Industry and settlement by continetal region; 8 continental regions, as in TAR, but Small Islands not Small Island States; Sub-regional summary maps for each region, using physiographic, biogeographic or geographic definitions; Example vulnerability maps at sub-national scale and globally by country.
		Mitigation: 17 global economic regions for GDP; Energy supply by continent, by economic regions, by 3 UNFCCC groupings; Trends in CO_2 emissions (and projections) , waste and carbon balance by economic regions.
***SR**: Renewable Energy Sources and Climate Change Mitigation* [23]	2012	Global maps showing potential resources for renewable energy: land suitability for bioenergy production, global irradiance for solar, geoethermal, hydropower, ocean waves/tidal range, wind); Various economic/continental regions: installed capacity (realised vs. potential), types of technologies, investment cost, cost effectiveness, various scenario-based projections; Country comparisons of deployment and uptake of technologies, share of energy market.
***SR**: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [24]	2012	Trends in observed (tables) and projected (maps and tables) climate extremes (Tmax, Tmin, heat waves, heavy precipitation and dryness) by 26 sub-continental regions covering most land areas of the globe; Attribution studies of return periods of extreme temperatures for 15 "Giorgi-type" regions; Gridded global maps of projected extremes of temperature, precipitation, windspeed, dry spells and soil moisture anomalies; Continental-scale estimates of projected changes in impacts of extremes (floods, cyclones, coastal inundation) as well as frequencies of observed climate extremes and their estimated costs); Distinctions drawn between local, country and international/global actors with respect to risk management and its financing.
***Fifth Assessment Report (AR5)** – this assessment*	2014	*Climate*:
		Impacts, adaptation and vulnerability: Nine continental-scale regions, eight as in AR4 plus open oceans.
		Mitigation:

1. IPCC (1990c); 2. IPCC (1990a); 3. IPCC (1990b); 4. IPCC (1992b); 5. IPCC (1992a); 6. IPCC (1994) 7. IPCC (1996c); 8. IPCC (1996b); 9. IPCC (1996a); 10. IPCC (1998b); 11. IPCC (1998a); 12. IPCC (1999); 13. IPCC(2000a), 14. IPCC (2000b); 15. IPCC (2001c); 16. IPCC (2001a); 17. IPCC (2001b); 18. IPCC/TEAP (2005); 19. IPCC (2005); 20. IPCC (2007c); 21. IPCC (2007a); 22. IPCC (2007b); 23. IPCC (2012b); 24. IPCC (2012a)

Table 21-3: Two possible entry points for thinking about vulnerability to climate change (adapted from Füssel 2007).

Context	Climate change impacts perspective	Vulnerability perspective
Root problem	Climate change	Social vulnerability
Policy context	Climate change mitigation, compensation, technical adaptation	Social adaptation, sustainable development
Illustrative policy question	What are the benefits of climate change mitigation?	How can the vulnerability of societies to climatic hazards be reduced?
Illustrative research question	What are the expected net impacts of climate change in different regions?	Why are some groups more affected by climatic hazards than others?
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to current climate variability
Starting point of analysis	Scenarios of future climate change	Current vulnerability to climatic stimuli
Analytical function	Descriptive, positivist	Explanatory, normative
Main discipline	Natural science	Social science
Meaning of 'vulnerability'	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors
Vulnerability approach	Integrated, risk-hazard	Political economy
Reference	McCarthy et al (2001)	Adger (1999)

Table 21-4: Dimensions of assessments of impacts and vulnerability and of adaptation drawn upon to serve different target audiences (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to the original studies and to the chapters in which they are cited. Aspects of some of the studies in this table are also alluded to in section 21.5.

Approach/audience: Scale:	Impacts/vulnerability	Adaptation	Target audience
Global	Resource availability[1,2,3] Impact costs[4,5,6,7] Vulnerability/risk mapping[8,9,10] Hotspots analysis[11]	Adaptation costs[4,5,7]	- Policy negotiations - Development aid - Disaster planning - Capacity building
Continental/ biome	Observed impacts[12,13,14] Future biophysical impacts[15,16] Impact costs[5,15] Vulnerability/risk mapping[17]	Adaptation costs[5] Modelled adaptation[18]	- Capacity building - International law - Policy negotiations - Regional development
National/ state/province	Observed impacts[19,20,21] Future impacts/risks[22,22,23] Vulnerability assessment[23] Impact costs[24]	Observed adaptation[25] Adaptation assessment[23,26]	- National adaptation plan/strategy - Nat. Communication - Legal requirement - Regulation
Municipality/ basin/patch/ delta/farm	Hazard/risk mapping[27] Pest/disease risk mapping[28] Urban risks/vulnerabilities[29]	Adaptation cost[27] Urban adaptation[29,30]	- Spatial planning - Extension services - Water utilities - Private sector
Site/field/tree/ floodplain/ household	Field experiments[31]	Coping studies[32,33] Economic modelling[34] Agent-based modelling[35]	- Individual actors - Local planners

Notes for Table 21-4

[1] Global terrestrial water balance, in the Water Model Intercomparison Project (Haddeland *et al*., 2011), see chapter 3

[2] Global dynamic vegetation model intercomparison (Sitch *et al*., 2008), see chapter 4

[3] Impacts on agriculture, coasts, water resources, ecosystems and health in the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP – Schiermeier, 2012), see chapter 19

[4] UNFCCC study to estimate the aggregate cost of adaptation (UNFCCC, 2007), which is critiqued by Parry (2009) and Fankhauser (2010).

[5] The Economics of Adaptation to Climate Change study (World Bank, 2010).

[6] Chapter 17 provides a thorough evaluation of global modelling studies (see also chapters 14 and 16)

[7] Impacts on agriculture and costs of adaptation (e.g. Nelson *et al*., 2009), see chapter 7

[8] Quantifying and Understanding the Earth System (QUEST) Global-scale impacts of climate change (GSI) project (Arnell *et al*., submitted) [not cited in FOD chapters]

[9] OECD project on Cities and Climate Change (Hanson *et al*., 2011), see chapters 5, 23, 24 and 26

[10] For critical reviews of global vulnerability studies, see Füssel (2010) and Preston et al.(2011)

[11] A discussion of hotspots can be found in section 21.3.3, with a critique in section 21.5.3

[12] Satellite monitoring of sea ice over polar regions (Comiso and Nishio, 2008), see also Comiso (in prep.) and chapters 18 and 28

[13] Satellite monitoring of vegetation growth (e.g., Piao *et al*., 2011) and phenology (e.g., Heumann *et al*., 2007), see chapters 4 and 18

[14] Meta-analysis of range shifts in terrestrial organisms (e.g., Chen *et al*., 2011), see chapters 4 and 18

[15] Physical and economic impacts of future climate change in Europe (Ciscar *et al*., 2011), see chapter 23

[16] Impacts on crop yields in West Africa (Roudier *et al*., 2011) [not cited in FOD chapters]

[17] Climate change integrated methodology for cross-sectoral adaptation and vulnerability in Europe (CLIMSAVE) project (Harrison *et al*., 2012), see Chapter 23

[18] Modelling agricultural management under climate change in sub-Saharan Africa (Waha *et al*., 2013) [not cited in FOD chapters]

[19] Satellite monitoring of lake levels in China (Wang *et al*., 2013) [not cited in FOD chapters]

[20] Satellite monitoring of rice phenology in India (Singh *et al*., 2006), see chapter 18

[21] UK Climate Change Risk Assessment (CCRA, 2012), see chapter 23

[22] United States Global Change Research Program second (Karl *et al*., 2009) and third (in review) national climate change impact assessments, see chapter 26

[23]The Global Environment Facility (GEF)-funded Assessments of Impacts and Adaptations to Climate Change (AIACC) program addressed impacts and vulnerability (Leary *et al*., 2008b) and adaptation (Leary *et al*., 2008a) in developing countries, see chapter 27

[24] Economics of Climate Change national studies in Kenya and Tanzania (SEI, 2009; GCAP, 2011)[not cited in FOD chapters]

[25] Sowing dates of various crops, Finland (Kaukoranta and Hakala, 2008) [not cited in FOD chapters]

[26] Finnish Climate Change Adaptation Research Programme (ISTO) Synthesis Report (Ruuhela, 2012)

[27] Urban flood risk and adaptation cost, Finland (Perrels *et al*., 2010) [not cited in FOD chapters]

[28] See Garrett (2013) for a specific example of a risk analysis, or Sutherst (2011) for a review – and see chapter 25.

[29] New York City coastal adaptation (Rosenzweig *et al*., 2011), see chapters 8 and 26

[30] Bangkok Assessment Report of Climate Change (BMA/GLF/UNEP, 2009), see chapters 8 and 24

[31] Field, chamber and laboratory plant response experiments (e.g., Long *et al*., 2006; Hyvönen *et al*., 2007; Wittig *et al*., 2009; Craufurd *et al*., 2013), see chapters 4 and 7

[32] Farming response to irrigation water scarcity in China (Liu *et al*., 2008) and see chapter 13

[33]Farmers' mechanisms for coping with hurricanes in Jamaica (Campbell and Beckford, 2009) and see chapter 29

[34] Modelling micro-insurance of subsistence farmers for drought losses in Ethiopia (Meze-Hausken *et al*., 2009) [not cited in FOD chapters]

[35] Simulating adaptive behaviour of farming communities in the Philippines (Acosta-Michlik and Espaldon, 2008), see chapter 24

Table 21-5: Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to Very Low (VL). Reliability of information on past climate depends on the availability and quality of observations and in general is higher for temperature as it is easier to observe and a temperature observation at a given location is more representative of temperatures in the surrounding areas than a precipitation observation. In the case of future climate change, which relies on using models of the climate system run into the future, reliability depends on the ability of these models to simulate well the processes that lead to these changes. Again, information on temperature is generally more reliable but this is due to there being more confidence in our ability to simulate the past changes in temperature and our understanding of the processes that cause these changes than is the case for precipitation.

There are significant variations in the reliability of past and future climate information at different temporal and spatial scales, in general at finer scales the information tends to be less reliable given the need for either a greater density observations or models maintaining accuracy at high resolutions. Also, there are significant geographical variations, again the root cause being different for information on past climate than on future climate change. For past climate observation availability and quality is again key and in many regions, especially for precipitation, there are issues with either or both. For future climate change, data availability is less of an issue with the advent of large ensembles of climate model projections but quality can be a significant problem in some regions where the models perform poorly and there is little confidence that the processes driving the projected changes are accurately captured.

Scale	**Temporal**	**Annual**		**Seasonal-Monthly**		**Daily**	
Spatial	**Variable / Era**	**Temp**	**Precip**	**Temp**	**Precip**	**Temp**	**Precip**
Global	Past	VH	H	VH	H	N/A	N/A
	Future change	VH – direction H – amount	H – direction MH – amount	VH – direction H – amount	H – direction MH – amount	N/A	N/A
Regional, Large river basin	Past	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability
	Future change	VH – direction H – amount	H-L depends on capture of processes	VH – direction H – amount	H-L depends on capture of processes	VH – direction MH – amount	H-L depends on capture of processes
National, State	Past	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability
	Future change	VH – direction H – amount	H-L depends on capture of processes	VH – direction H – amount	H-L depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes
City, County	Past	VH-H depends on observation availability	H-VL depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability	H-MH depends on observation availability	H-VL depends on observation availability
	Future change	H – direction MH – amount	H-VL depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes	H – direction M – amount	M-VL depends on capture of processes
Village, Site/field	Past	VH-H depends on observation availability	H-VL depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability	H-MH depends on observation availability	H-VL depends on observation availability
	Future change	H – direction MH – amount	H-VL depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes	H – direction M – amount	M-VL depends on capture of processes

Table 21-6: Placeholder for a table to be derived from the AR5 WG1 Ch14 table (still in development by WG1) evaluating confidence in GCM simulations and projections of temperature and precipitation and linked regional climate phenomena currently being finalised for the final draft of that chapter.

Table 21-7: Leading knowledge gaps and related research needs.

	Knowledge Gap	Research need
1	There is no clear understanding of how to integrate the data products from multi-model multi-method research for producing climate change projections. This results in data products of conflicting time and space resolution scales, with differing dependencies and assumptions, and resultant non-equivalency of variables. At present each product is individually plausible and mostly defensible in-so-far as it has physical basis within the assumptions of the method. However, at decision-relevant scales the products collectively indicate a wide range of outcomes with high uncertainty and contradictions and are thus not strongly actionable.	The approaches on how to understand the source of spread and contradiction in the information at scales relevant to users. This raises the strong need to find ways to identify the value signal within the noise of the multi-model multi-method climate projections methods, and build robust messages that are user-relevant and actionable.
2	Limits to predictive information. The community engaged in developing regional climate change projections have forded ahead with increasing sophistication of tools and models, yet at the regional and adaptation decision scales the signal to noise ratio has not advanced commensurately (e.g. Maslin and Austin, 2012). The inherent uncertainty of the emerging projections is poorly articulated (or even absent), and where provided is likely an under-estimate of the true range of uncertainty.	Means to identify the limit of predictive information, and/or articulate the real uncertainty inherent in and information product, are important to inform response to climate change, and understand when climate information is useful at the scales of need. Research is critically needed to distinguish apart the inherent blend of stochastic and deterministic variability and change of the regional climate, which is intrinsically a function of scale, variable, and application.
3	The attributes of regional change through which impacts are manifest, such as the intensity, persistence, distribution, recurrence, and frequency, are poorly understood. The information conveyed to the adaptation community is dominated by aggregates in time and space (e.g. SREX regional averages, or time averages), which hide the important attributes underlying these aggregated changes. In part this is a consequence of (1) and (2) above.	The research need is for greater nuance in the understanding of the data to unpack the regional projections into terms relevant for impacts and adaptation. For example, how is the shape of the distribution of weather events changing (not just the extremes), or information on the stability of critical global teleconnection patterns that contribute to the variability of a region.
4	The historical record for many regions, especially those regions most vulnerable to climate change, is poor to the extent that the historical record is at best an estimate with unknown uncertainty. This severely undermines the development of regional change analysis, limits the evaluation of model skill, and presents a weak baseline against which to assess change signals.	The research need focuses on how to best integrate the multiplicity of historical data, including data rescue, raw observations, processed gridded products (e.g. CRU and GPCP), satellite data, and reanalysis data sets. For any given region data sets present different views of the past, and may even contradict each other. Research such as Zhang et al (2012), which evaluates different reanalysis products, indicates the value that can be attained for advancing understanding of the data veracity at regional scales.
5	Model projections of regional climate change impacts seldom have uncertainty ranges attached to estimates. Even if these are provided, they rarely distinguish the relative contributions of impact model uncertainty and climate projection uncertainty.	There is a need for more rigorous and comprehensive uncertainty analysis of impact models, accounting for both parameter and structural uncertainties. Model inter-comparison exercises offer one means for examining structural uncertainty.
6	Model sensitivity studies and inter-comparison exercises are beginning to reveal fundamental flaws and omissions in some impact models in the representation of key processes that are expected to be important under projected climate changes. For example, high temperature constraints, and CO2 and drought effects on agricultural yields are poorly represented in many crop models.	New field and chamber experiments are required, with controlled atmospheric composition and climate conditions, using modern and potentially adapted cultivars, to improve understanding of key processes operating in crop plants and soils under changed environments. Such experiments are needed across a range of biogeographical and edaphic zones in different regions of the world.
7	New global scenarios are under development, based on climate projections for different representative concentration pathways (RCPs) and socio-economic scenarios based on shared socio-economic pathways (SSPs). However, there is currently little or no guidance on how these projections are to be accessed or applied in IAV studies. Moreover, as yet, quantitative SSPs are available only for large regions (basic SSPs), and regional SSPs that are consistent with the global SSPs have not yet been developed (extended SSPs).	Extended SSPs for major sub-continental regions of the world, including variables that define aspects of adaptive capacity and guidance on how to combine RCP-based regional climate projections with regional SSPs to form plausible regional scenarios for application in IAV analysis.

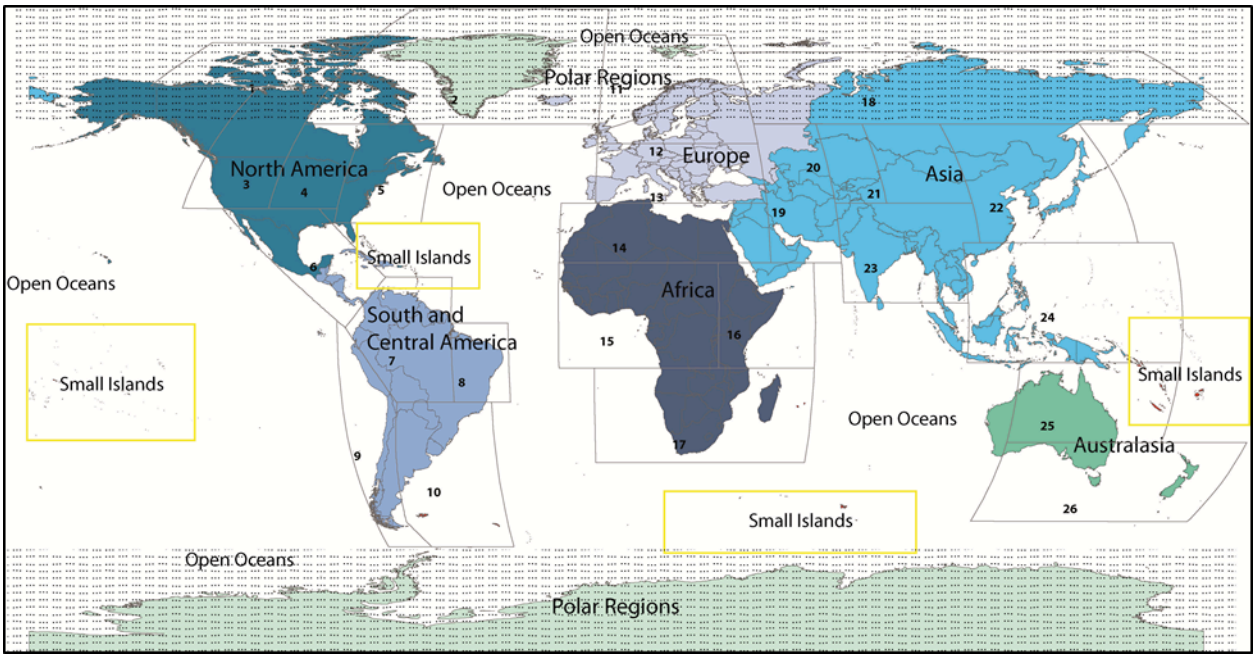


Figure 21-1: Map showing regions described in chapters 22-30 of Part B (colours) with numbered [26] open polygons defining sub-regions over land used to summarise projected changes in climate in this chapter Note that regional specifications are approximate, as aspects of some regions or territories are treated in more than one chapter. Supplementary material contains more details of chapter assignment (Table S21-1) as well as co-ordinates of the polygons (Table S21-2).

Figure 21-2: Entry points for adaptation science, policy, and practice (based on Hinkel et al, submitted).

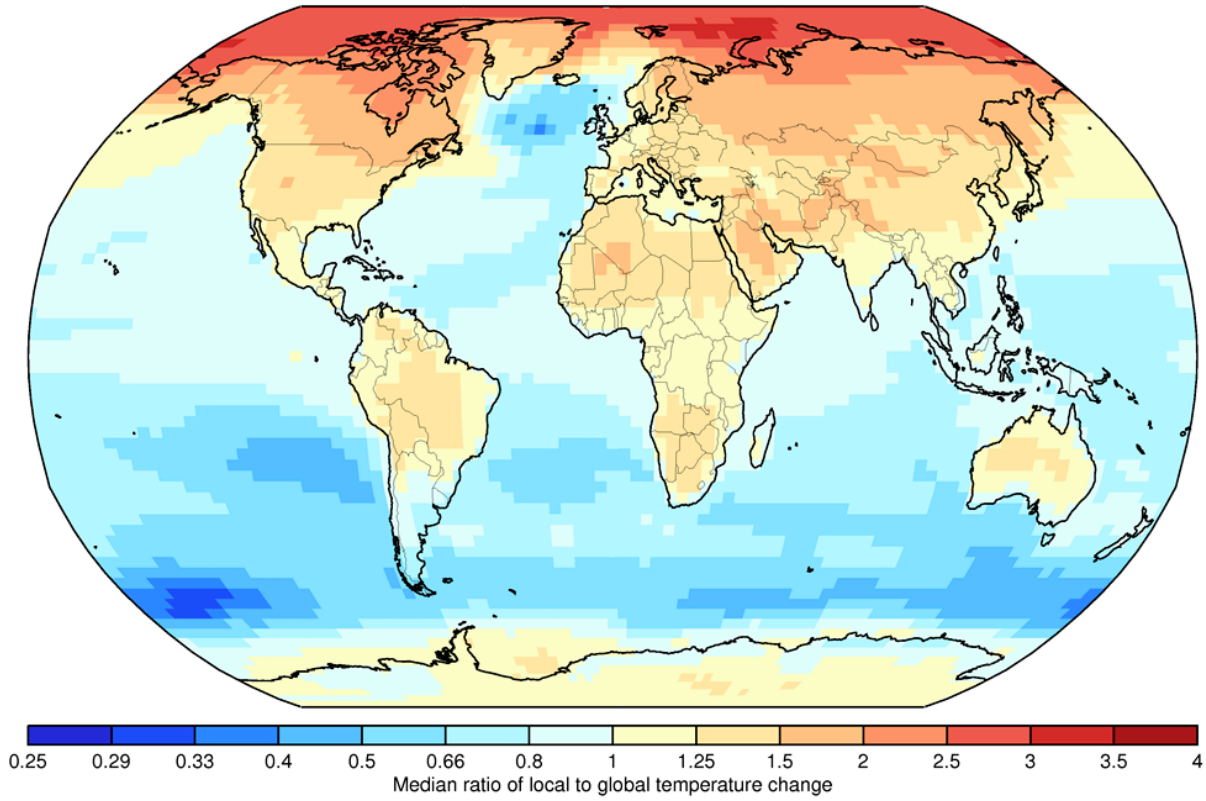


Figure 21-3. CMIP5 ensemble median ratio of local:global average temperature change in the period 2070-2100 relative to 1961-90 under the RCP8.5 emissions/concentrations scenario. The values are displayed on a common 2.5ºx3.75º grid onto which each models' data were regridded and they were calculated as follows:
1) For each model calculate the local change between 1961-90 and 2070-2100 at each grid cell and divide by the global average change over the same period;
2) identify the median value across the ensemble at each grid cell.

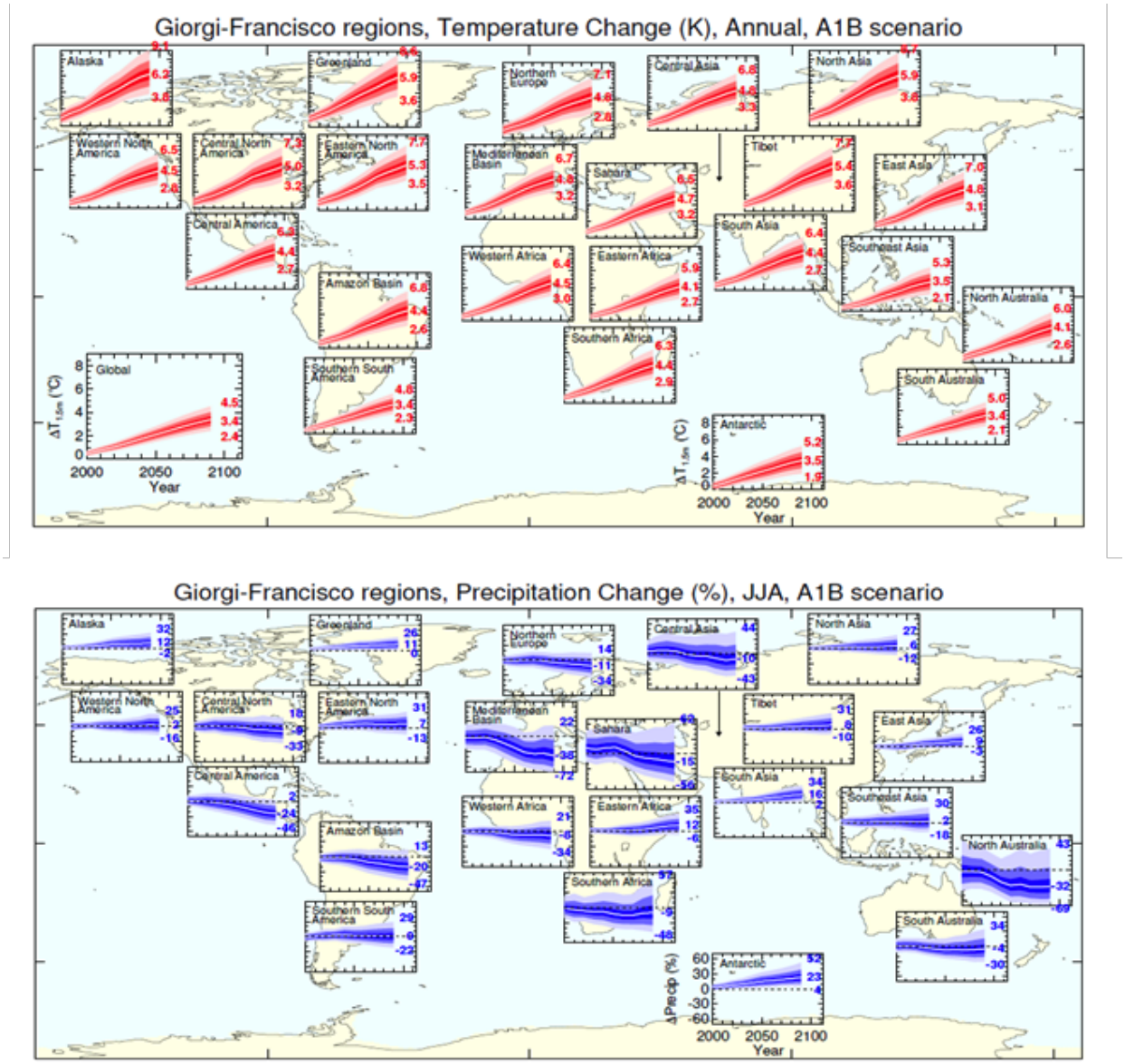


Figure 21-4: Evolution of the 5%, 17%, 33%, 50%, 66%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (upper panel) and annual precipitation (lower panel) for the Giorgi-Francisco (2000) regions and the globe with the A1B forcing scenario. Twenty year means relative to the 1961-1990 baseline are plotted in decadal steps using a common y-axis scale. The 5%, 50% and 95% percentile values for the period 2080-2099 are displayed for each region. (From Harris et al. 2012)

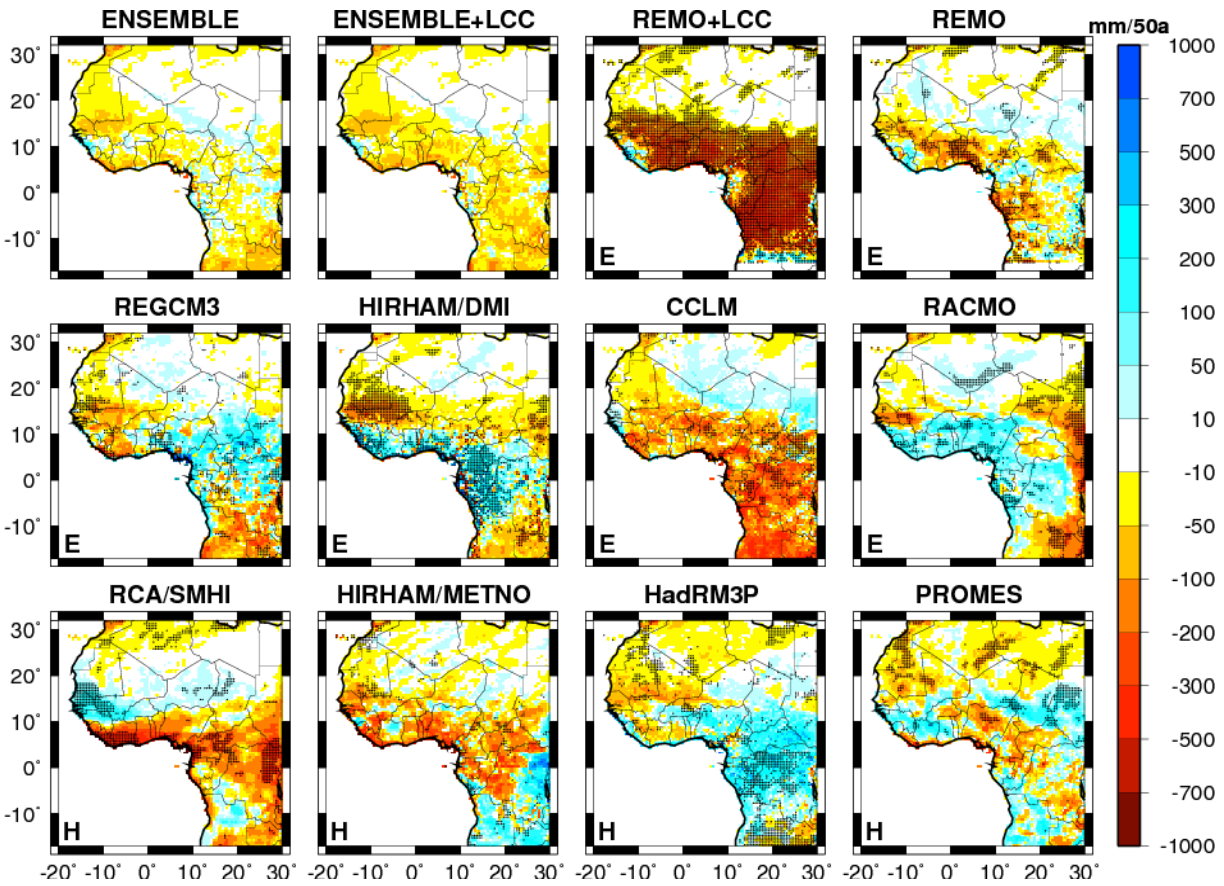


Figure 21-5: Linear changes (i.e. changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001-2050 period from 10 individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land cover changes (see Paeth et al. 2011 for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 5% level are marked by black dots. (From Paeth et al. 2011)

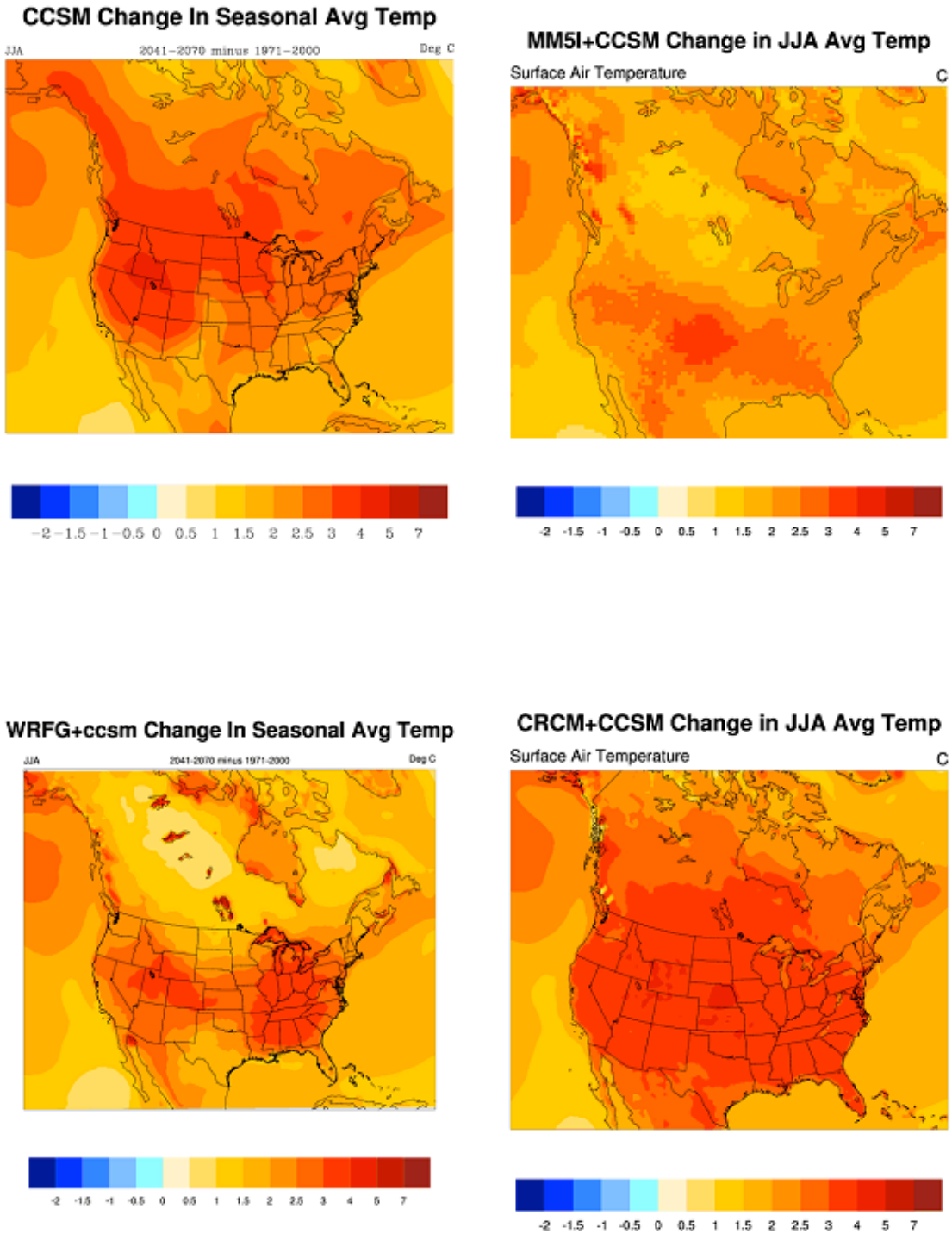


Figure 21-6: Change in summer (JJA) average temperature (2041-2070 minus 1971-2000) from (top left) the NCAR CCSM3, (top right) the MM5 regional climate model driven by the CCSM3; (bottom left) the WRF model, driven by CCSM3, and (bottom right) the Canadian CRCM, driven by CCSM3. Temperature is in °C. Data from the NARCCAP program. (From Mearns et al., 2009, 2013)

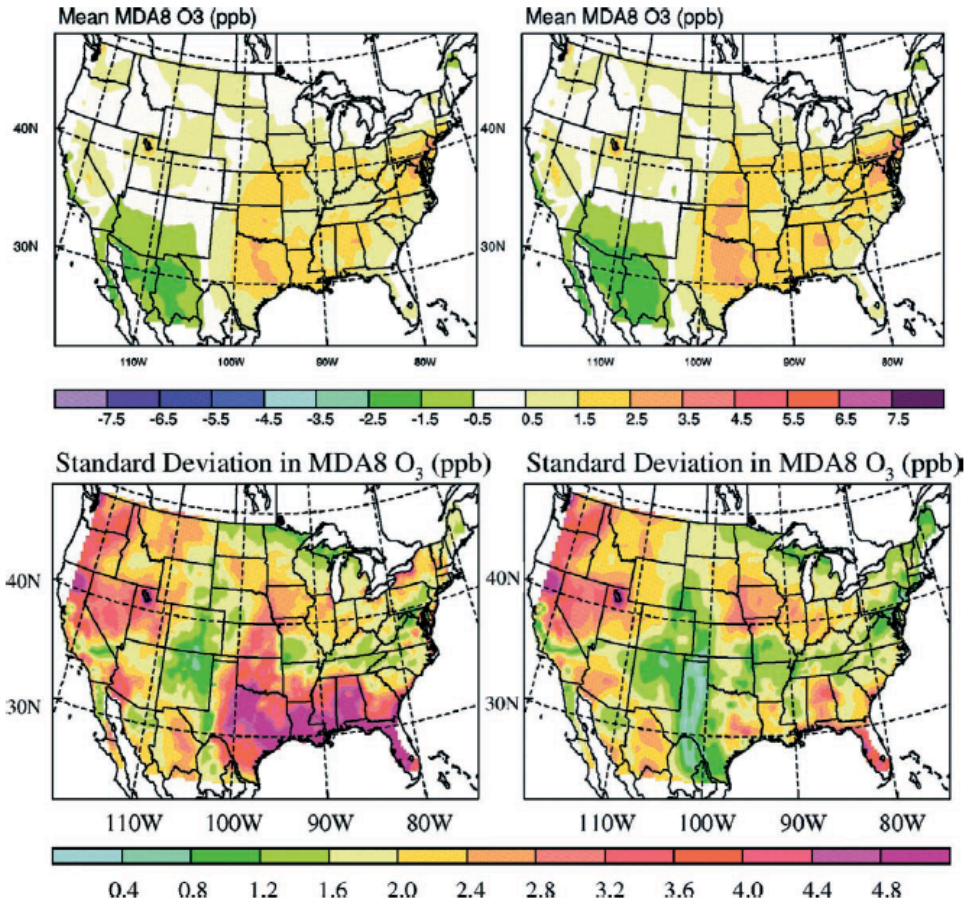


Figure 21-7: Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2081-2100 minus 1981-2000) MDA8 summer ozone concentrations across (left-hand panels) all 7 experiments (5 regional and 2 global) and, for comparison purposes (right-hand panels) not including the WSU experiment (which simulated July only conditions). (From Weaver et al. 2009)

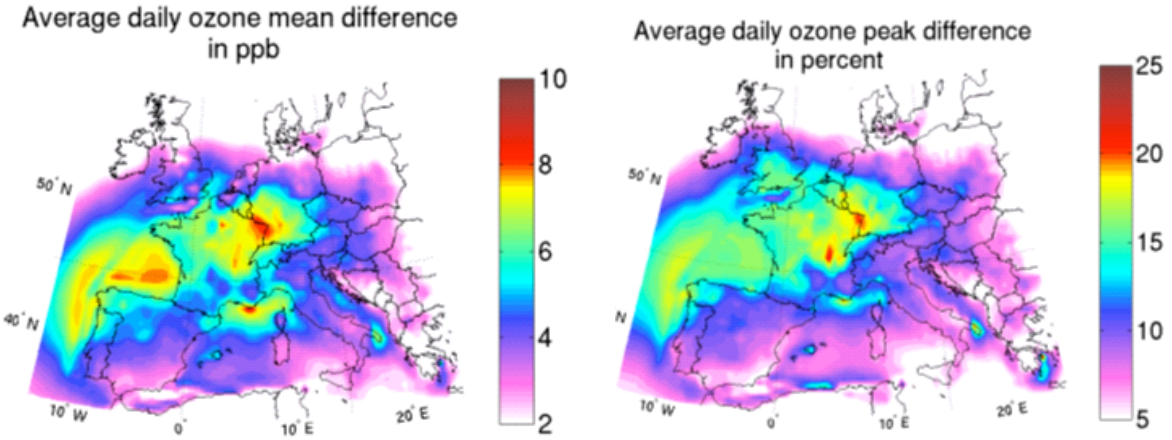


Figure 21-8: Difference in average summer daily ozone mean (left panel) and peak (right panel) concentration over Europe due to climate change, (2071-2100 minus 1961-1990), A2 scenario. (From Meleux et al. 2007)

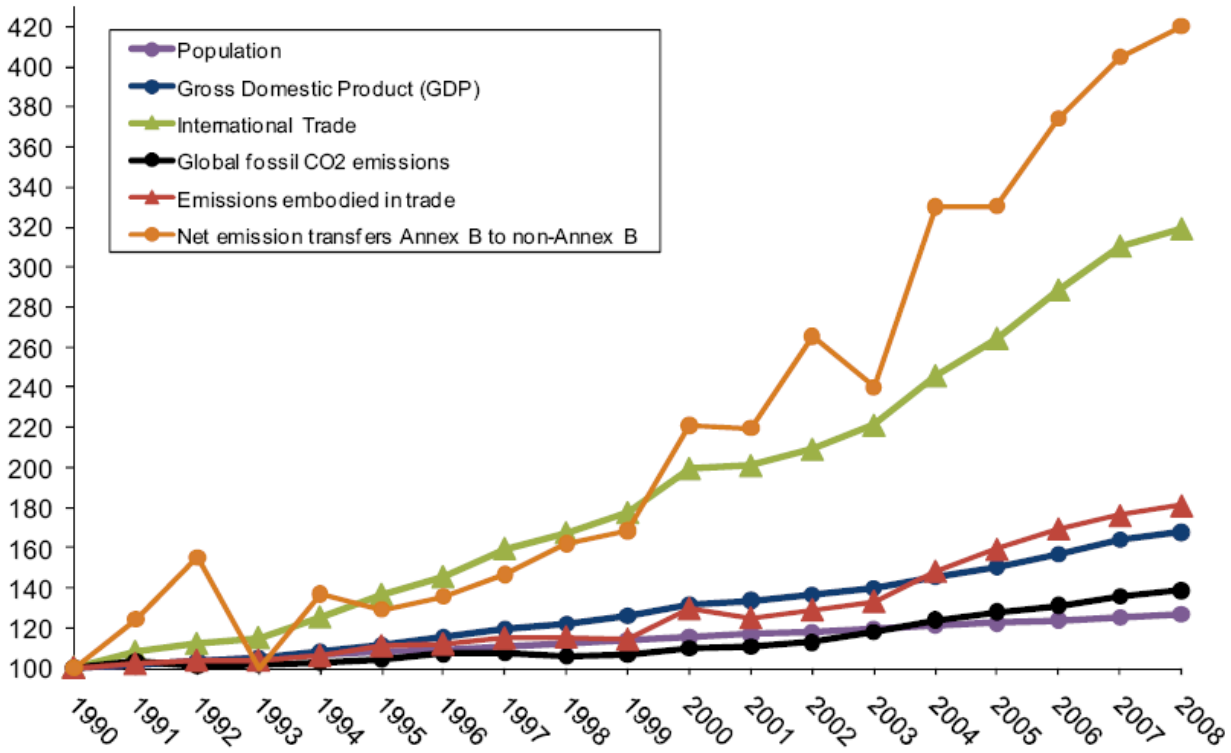


Figure 21-9: Growth rates from 1990-2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macrovariables, all indexed to 1990 (Peters et al., 2011).]

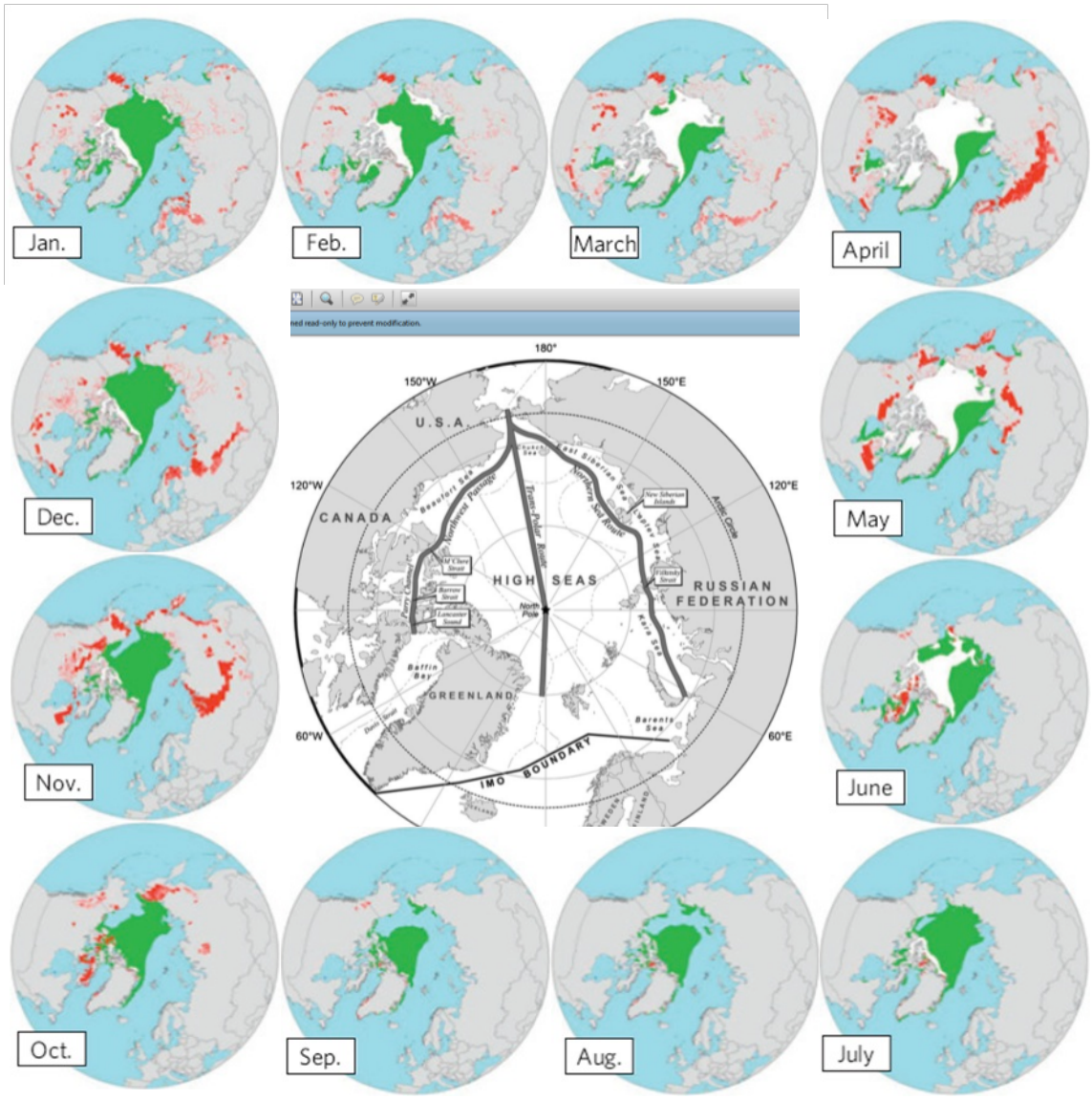


Figure 21-10: (a) Marine exclusive environmental zones (EEZs – dashed lines) of Canada, Greenland/Denmark, Norway, Russia, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the IMO Guidelines Boundary for Arctic shipping (thick black border). After Stephenson (2013). (b) Projected change in accessibility of maritime and land-based transportation by mid-century (2045-2059 relative to 2000-2014) using the Arctic Transport Accessibility Model and CCSM3 climate and sea ice estimates assuming an SRES A1B scenario. Green areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).

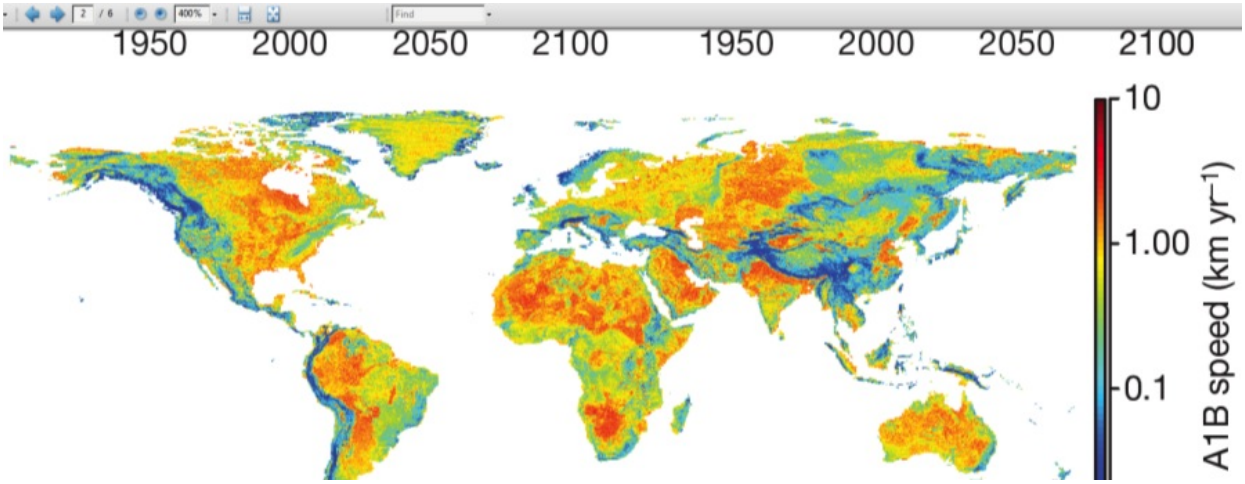


Figure 21-11: The velocity of shifting climatic zones due to climate change based on the average of 16 global climate models for an A1B emissions scenario and temporal gradients computed for 2050-2100. (Loarie et al., 2009).

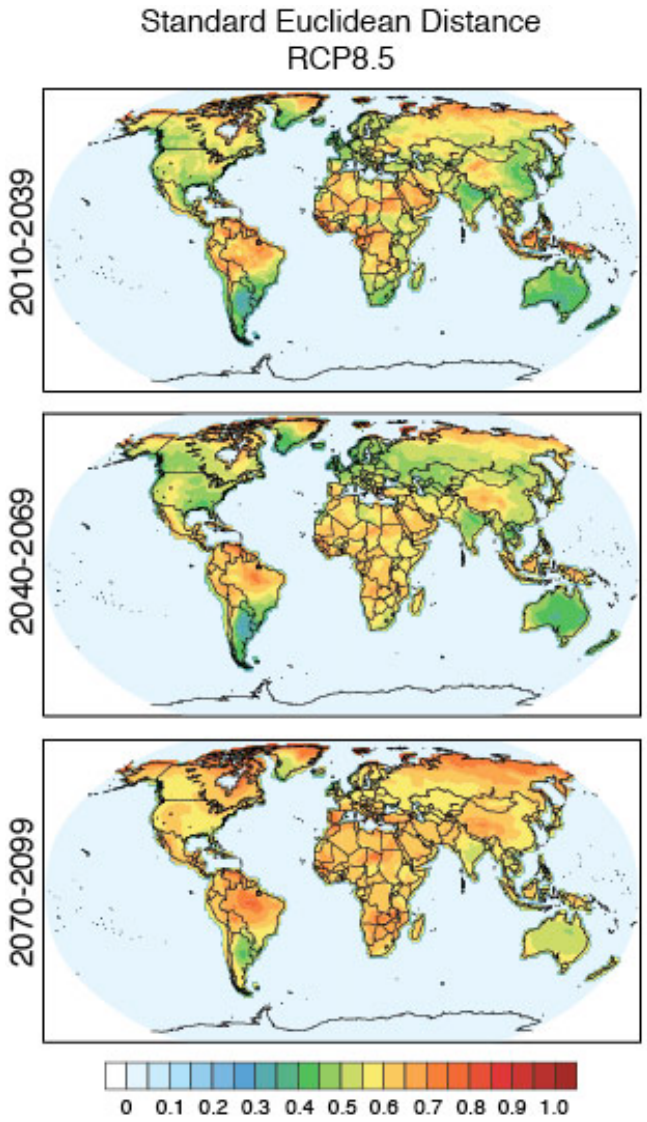
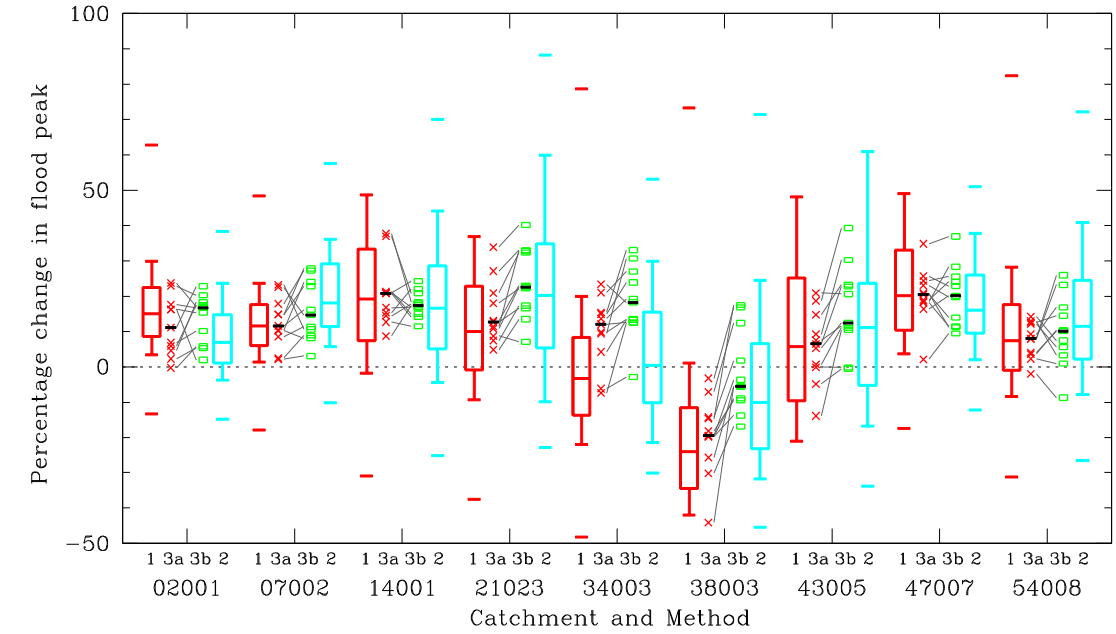


Figure 21-12: The relative aggregate climate change between the 1975-2005 period and the 2010-2039, 2040-2069 and 2070-2099 periods of RCP8.5. The aggregate climate change is calculated using the Standard Euclidean Distance (SED) across the 28-dimensional climate space formed by 7 climate variables in each of 4 seasons. The absolute values of change in each variable are normalized to the maximum global absolute value prior to calculating the SED. The SED values are then normalized to the maximum global SED value. Only land grid points north of 60˚S are used in the normalizations (From Diffenbaugh and Giorgi 2012).

a) 2-year return period



b) 20-year return period

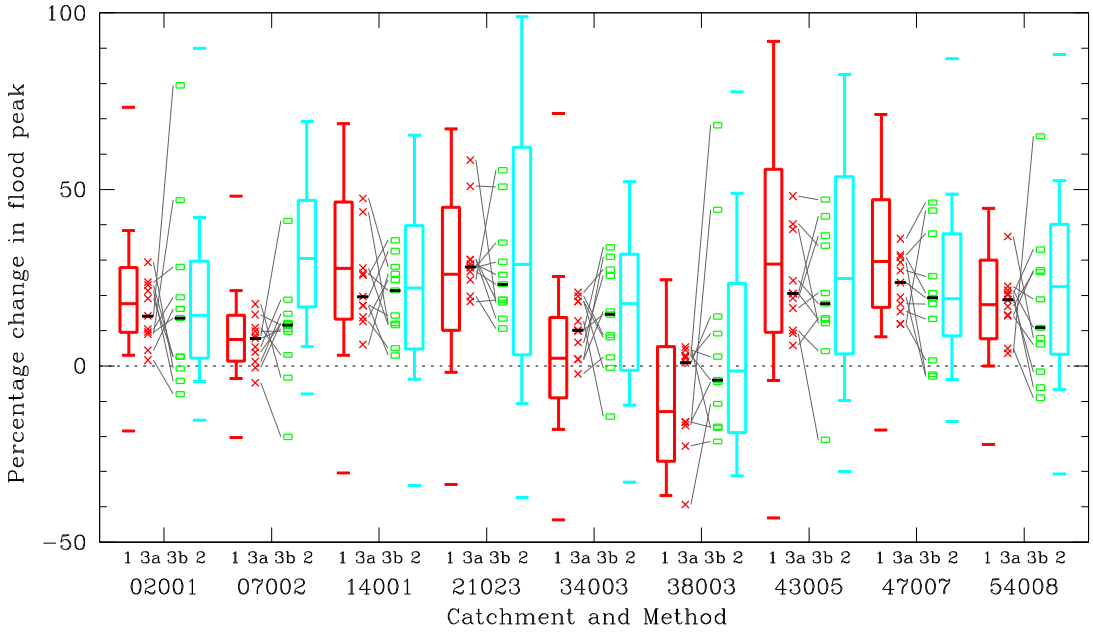


Figure 21-13: The range of percentage change in flood peaks for nine UK catchments at the a) 2-year and b) 20-year return period. Box-and-whisker plots are used to summarise results when using 10,000 UKCP09 Sampled Data (Murphy et al. 2009) change factors (red) and 100 sets of UKCP09 current and future Weather Generator time-series (cyan). Also plotted, are the results when using 11 sets of RCM-derived change factors (red crosses) and when using 11 sets of RCM current and future times-series (green rectangles). The box delineates the 25th-75th percentile range and the whiskers the 10th-90th percentile range, with the median (50th percentile) shown by the line dividing the box. Additional markers outside the whiskers indicate the minima and maxima, if within the plotted range of -50 to +100. The points derived from the RCM results are joined for the corresponding members of the RCM ensemble (grey lines), and the medians for these methods are shown by black horizontal bars.

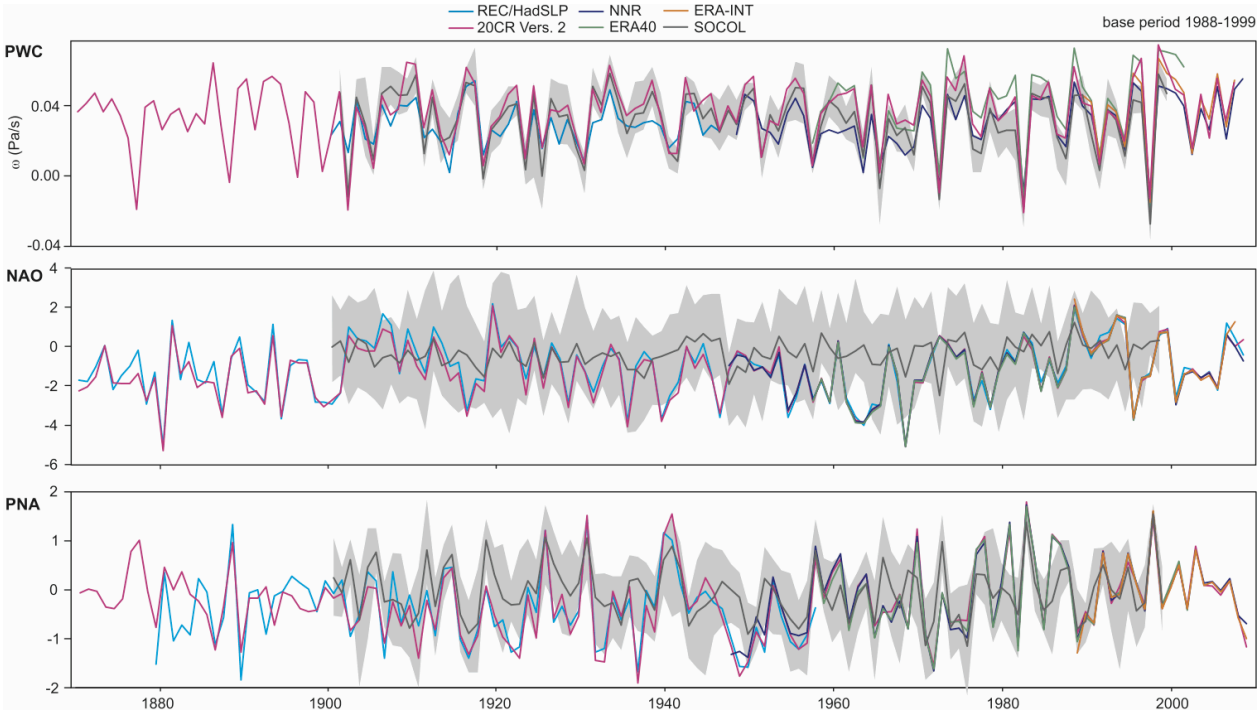


Figure 21-14: Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann etal. (2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis and model sources: statistical reconstructions of the PWC, the PNA and the NAO, see Brönnimann et al. (2009) for details, (all cyan); 20CR (pink); NCEP–NCAR reanalyses (NNR; dark blue); ERA-40 (green); ERA-Interim (orange). The dark-grey dashed line and grey shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed seas-surface temperatures and sea-ice from the HadISST dataset (Rayner et al. 2003), see Brönnimann etal. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea-surface temperature and sea-ice alone and demonstrate that the reanalyses have significantly higher skill in reproduces these modes of variability.

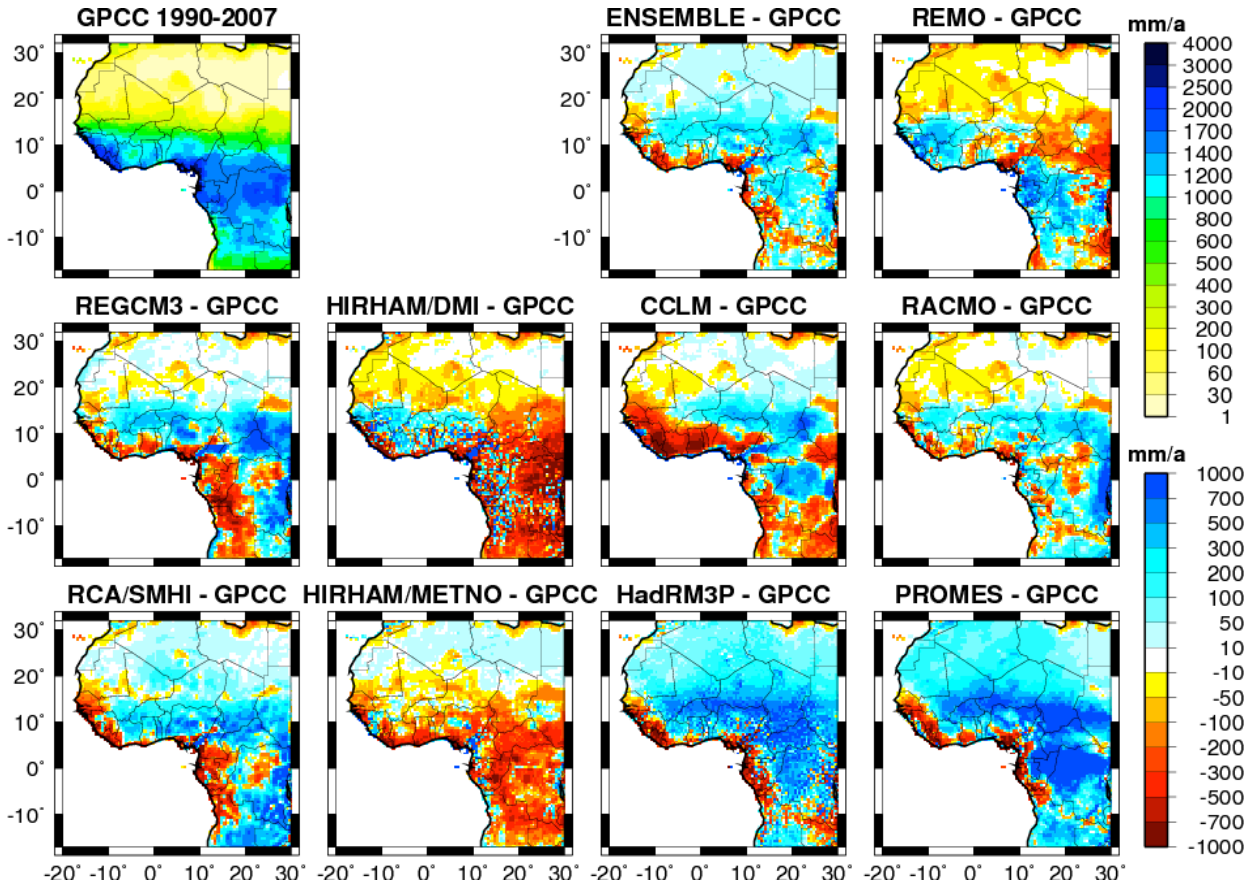
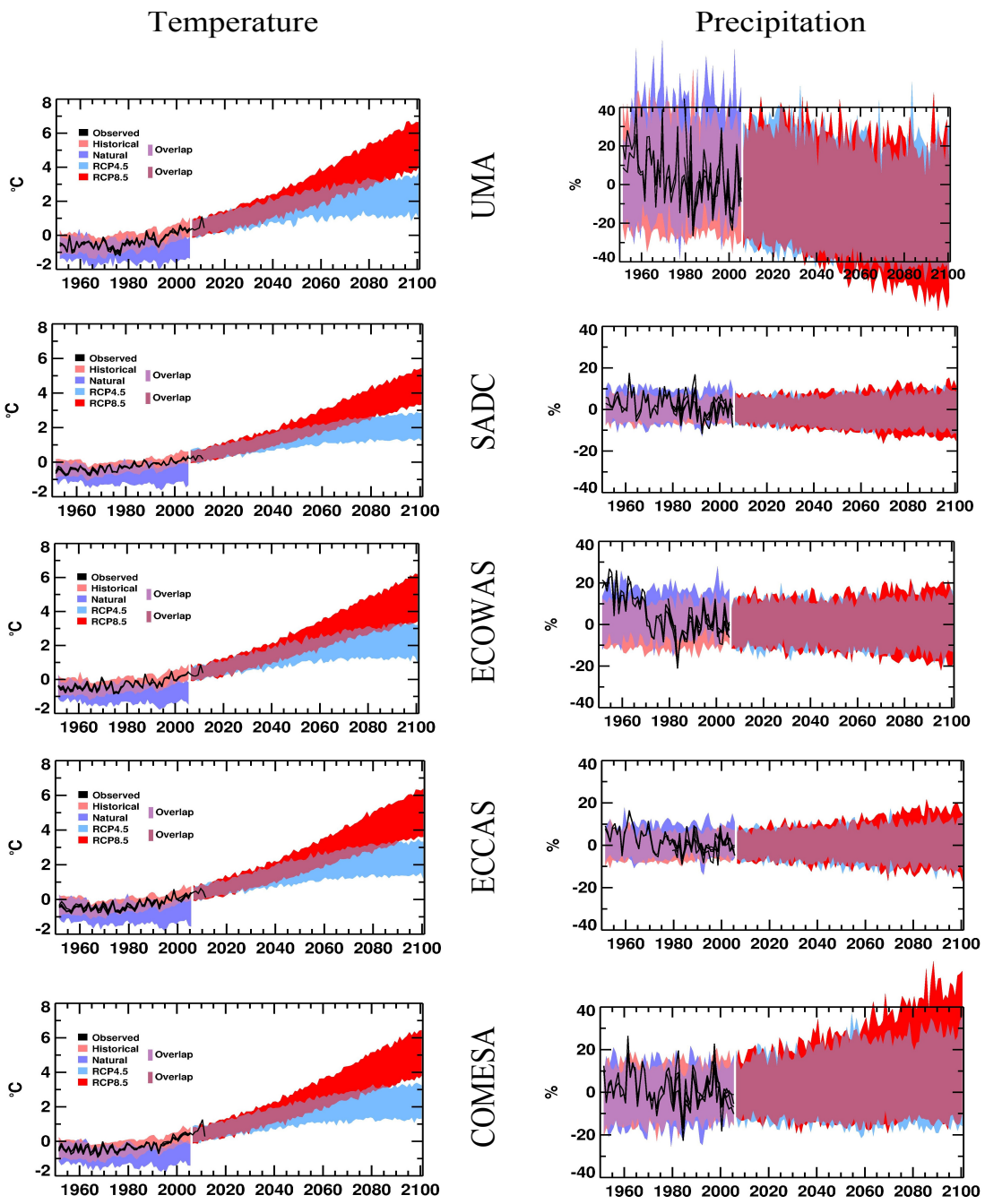


Figure 21-15: Observed 1990-2007 annual precipitation climatology from GPCC (Rudolf et al., 2011), top left, and, in the remaining panels, related systematic errors in 9 individual regional climate model simulations driven by the ERA-Interim reanalyses (Dee et al., 2011) and in the multi-model ensemble mean (Duryan et al., 2010).

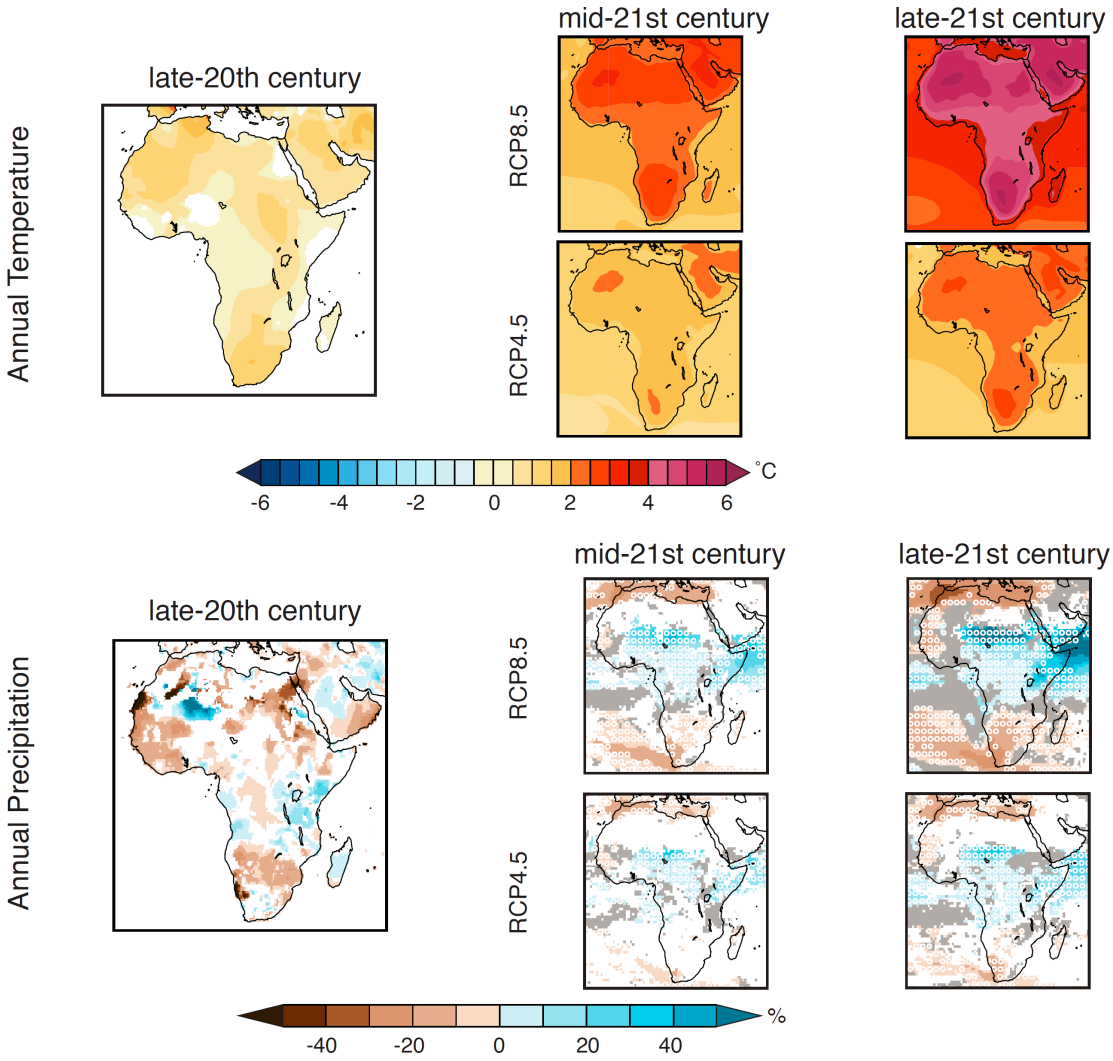
	Challenges to adaptation:		Low	Medium	High
			SSP1/SSP5	SSP2	SSP3/SSP4
	Reference	SRES	B1 /A1T / [A1FI]	B2	A2
RCP Replication	8.5 Wm^{-2}	A2 / A1FI	[A1FI]		A2
	6.0 Wm^{-2}	B2 / A1B		B2	
	4.5 Wm^{-2}	B1	B1 ← Mitigated SRES →		
	2.6 Wm^{-2}	[E1]	← Mitigated SRES →		

Box 21-1 Figure Caption: Approximate mappings of the SRES scenarios onto the new SSP/RCP framework (for details, see text). After Carter et al. (submitted).



Box 21-2 Figure Caption: Observed and simulated variations in past and projected future annual average precipitation and temperature over five African regions, Common Market for Eastern and Southern Africa (COMESA), the Economic Community of Central African States (ECCAS), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC) and the Arab Maghreb Union (UMA). Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations, taken from the CMIP5 archive (Taylor et al. 2012), driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30) and by two of the RCM emissions/ concentrations scenarios (van Vuuren et al., 2011), "RCP4.5" (68) and "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. The regions are described in Chapter 22 (section 22.1.2) but the COMESA region labelled here covers COMESA north and includes Rwanda, Uganda, and

Kenya. Precipitation is included for land territories only, while temperature is included for both land and exclusive economic zone territories. The observational datasets used are GISTEMP (Hansen et al. 2010), HadCRUT3 (Brohan et al. 2006), and MLOST (Smith et al. 2008) for temperature, and CMAP (Xie and Arkin 1997), CRU TS 3.10 (Mitchell and Jones 2005), GPCP v2.2 (Adler et al. 2003), and PRECL (Chen et al. 2002) for precipitation. These suffer in some areas from sparse monitoring coverage.



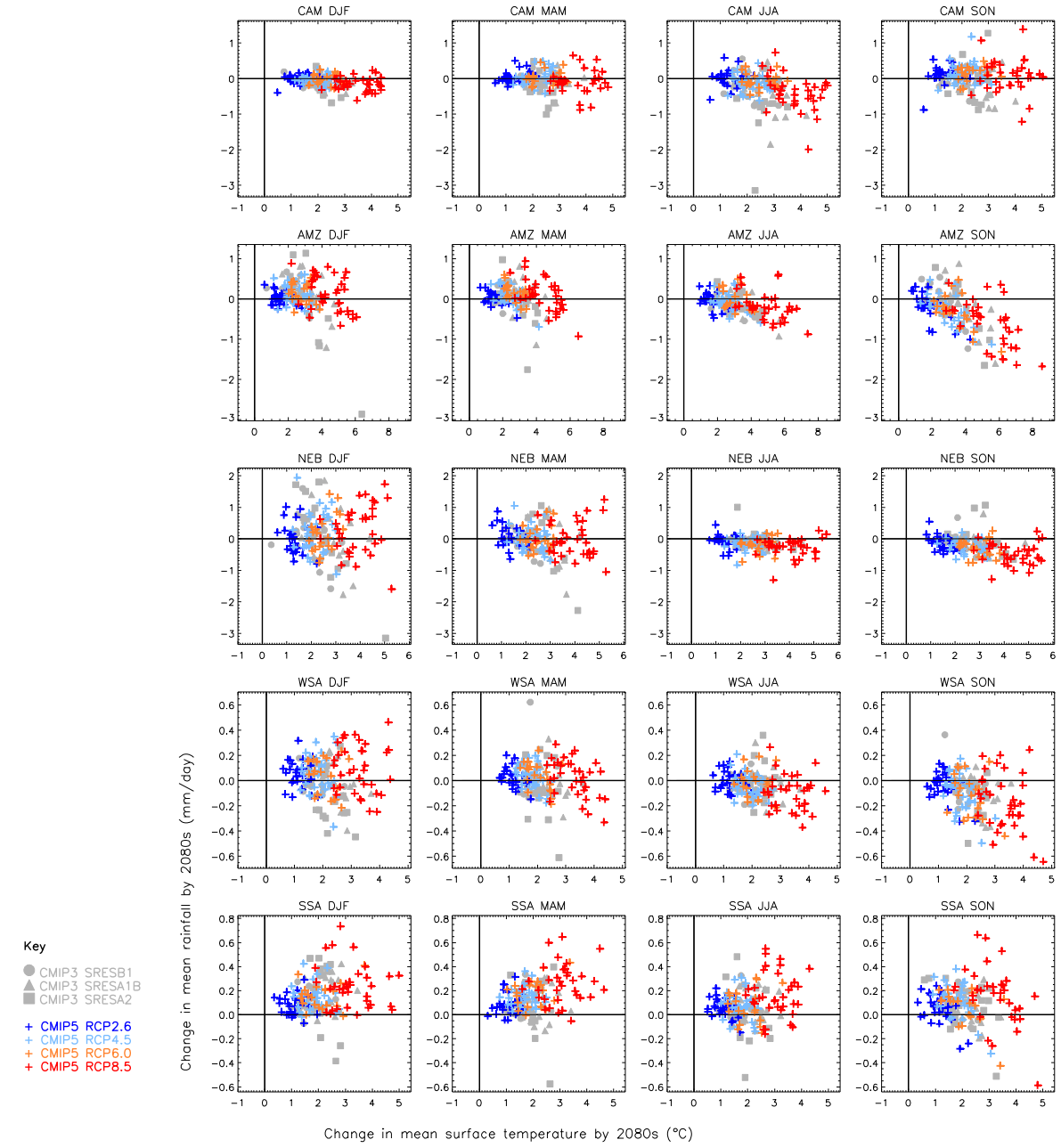
Box 21-3 Figure 1 Caption: Observed and projected changes in annual average temperature and precipitation over Africa. The observations are taken from the CRU TS 3.1 dataset (Harris et al., 2012) and the projections from the CMIP5 multi-model archive (Taylor et al. 2012). Projected changes are shown for the mid-21st century (2046-2065) and the late-21st century (2081-2100) from a baseline period of 1986-2005 under the RCP 4.5 and 8.5 emissions/ concentrations scenarios (van Vuuren et al., 2011). For the observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through to 1925. For the CMIP5 projections, four classes of results are displayed:

1) White indicates areas where for >66% of models the change in annual average precipitation is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986

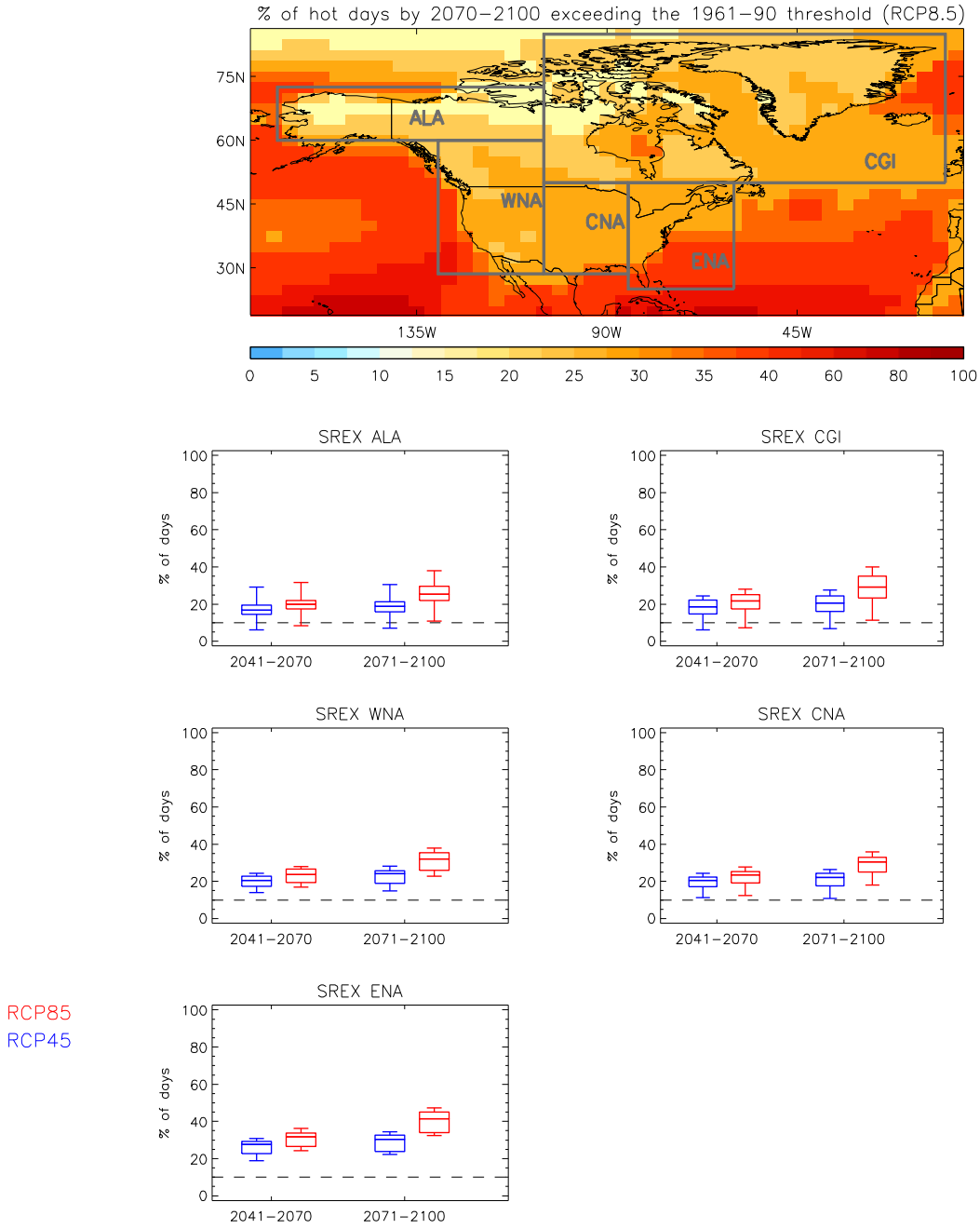
through 2005. Thus in these regions more than 2/3 of models show no significant change (using this measure of significance) in annual average precipitation. However, note that this does not imply no significant change in precipitation averaged over seasonal or shorter time-scales such as months to days.

2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation but less than 2/3 agree on whether annual average precipitation will increase or decrease.
3) Colors with circles indicate the change in annual average precipitation averaged over all models in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation and more than 2/3 agree (but less than 90%) agree on whether annual average precipitation will increase or decrease.
4) Colors without circles indicate the change in annual average precipitation averaged over all models in areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether annual average precipitation will increase or decrease.

For models which have provided multiple realizations for the climate of the recent past and the future, results from each realisation are first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated.

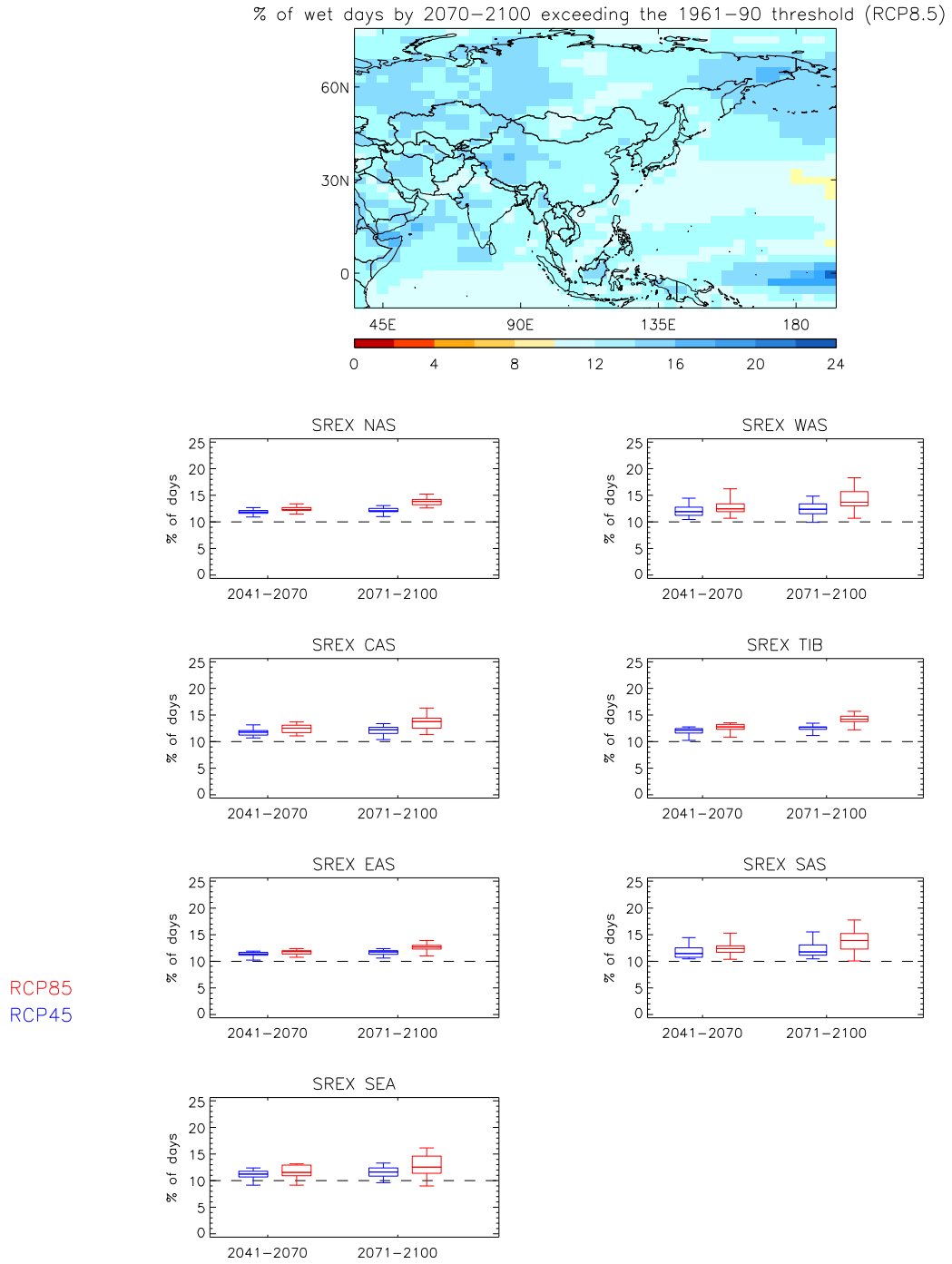


Box 21-3 Figure 2 Caption: Regional average change in seasonal mean temperature and precipitation over five regions covering South and Central America for the period 2070-2100 relative to 1961-90 in GCM projections from the CMIP5 ensemble under four RCP scenarios (van Vuuren et al., 2011) compared with GCM projections from the CMIP3 ensemble under three SRES scenarios (IPCC, 2000). Regional averaged are based on SREX region definitions (see Figure 21-RegAmplFac). Temperature changes are given in ºC and precipitation changes in mm/day with axes scaled relative to the maximum changes projected across the range of models.



[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]

Box 21-3 Figure 3 Caption: The frequency of 'hot days' (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961-1990) projected for the 2071-2100 period by the CMIP5 GCMs for North America. Top: Ensemble median frequency of 'hot days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'hot-day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of 'Hot days' of 10% is represented on the graphs by the dashed line.



[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]

Box 21-3 Figure 4 Caption: The frequency of 'very wet days' (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961-1990 with wet days defined as days with 1mm of precipitation or more) projected for the 2071-2100 period by the CMIP5 GCMs. Top: Ensemble median frequency of 'very wet days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'very wet day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of 'Very wet days' of 10% is represented on the graphs by the dashed line.

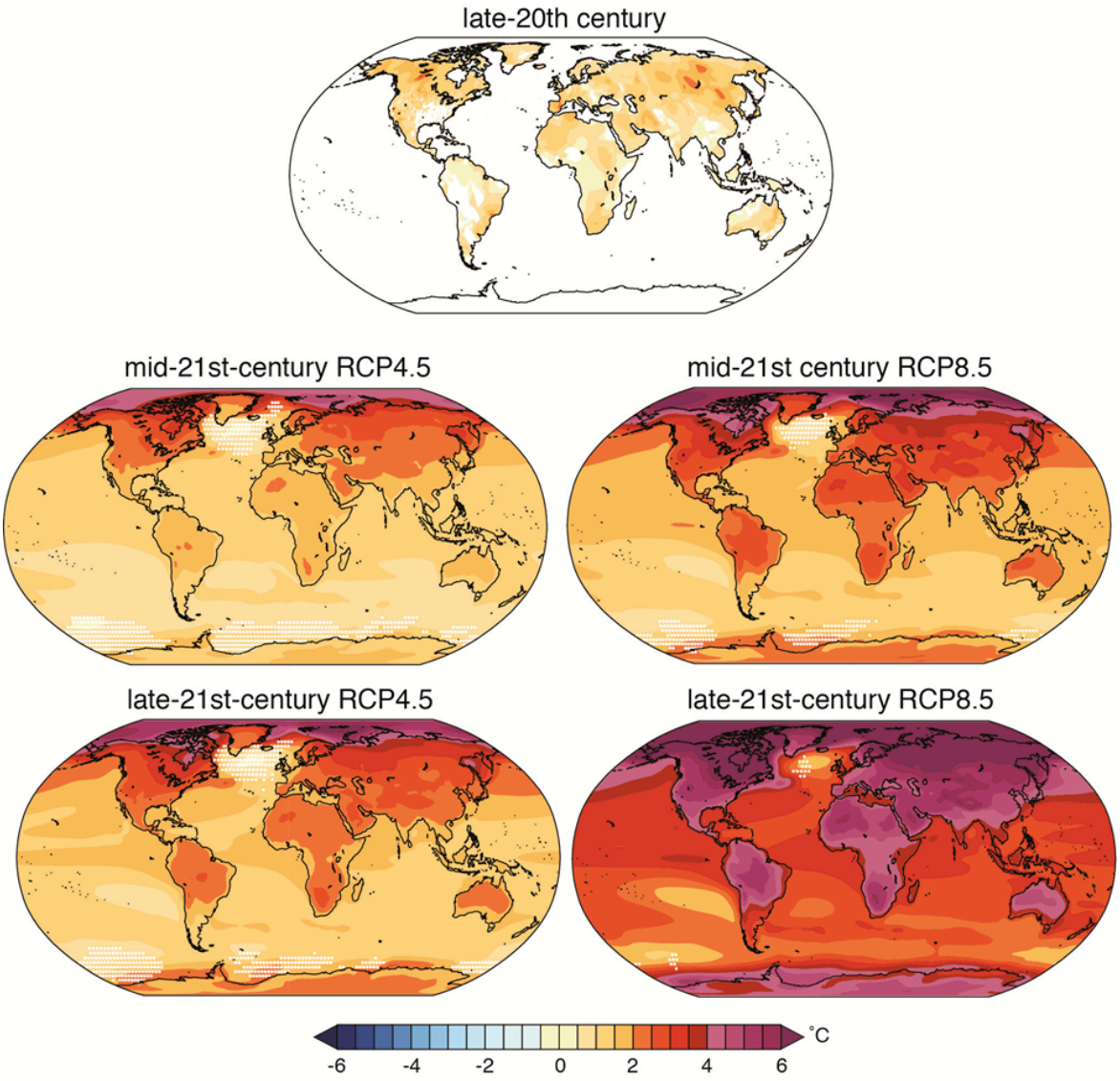


Figure RC-1: Change in annual temperature. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

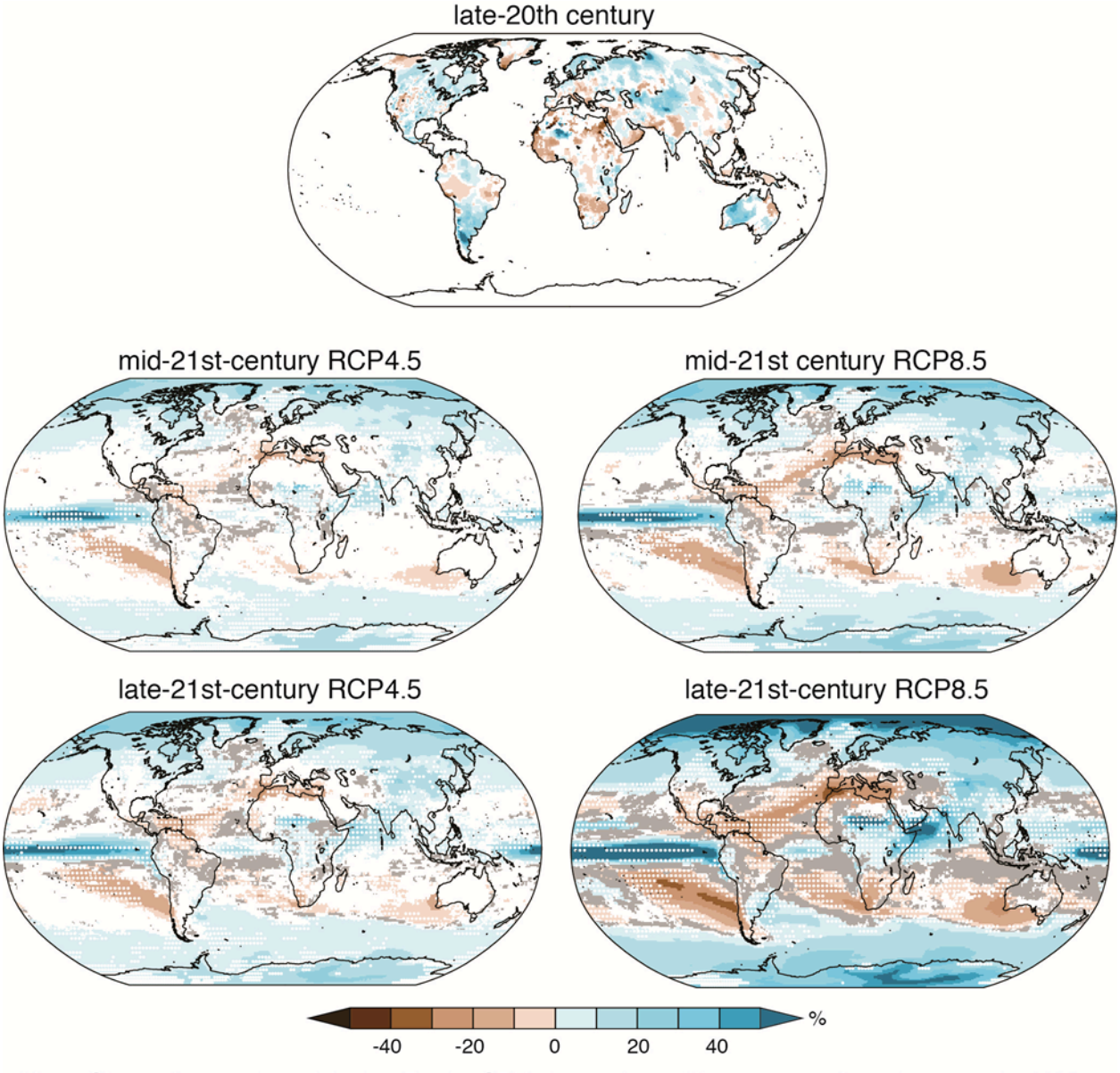


Figure RC-2: Change in annual precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

Chapter 22. Africa

Coordinating Lead Authors
Isabelle Niang (Senegal), Oliver C. Ruppel (Namibia)

Lead Authors
Mohamed Abdrabo (Egypt), Ama Essel (Ghana), Papa Demba Fall (Senegal), Jon Padgham (USA), Marie-Louise Rakotondrafara (Madagascar), Penny Urquhart (South Africa)

Contributing Authors
Ibidun Adelekan (Nigeria), Jane Battersby (South Africa), Michael Balinga (Cameroon), Mohammed Chahed (Tunisia), Monalisa Chatterjee (USA), Chineke Theo Chidiezie (Nigeria), Houria Djoudi (Algeria), Kristie L. Ebi (USA), Ricardo Fuentes (Mexico), Rebecca Garland (South Africa), Fatou Gaye (The Gambia), Emiloa Gbobaniyi (Nigeria), Patrick Gonzalez (USA), Blane Harvey (UK), Mary Hayden (USA), Andreas Hemp (Germany), Guy Jobbins (UK), Chris Lennard (South Africa), David Lobell (USA), Bruno Locatelli (France), Eva Ludi (UK), Lars Otto Naess (UK), Mzime R. Ndebele-Murisa (Zimbabwe), Aminata Ndiaye (Senegal), Andrew Newsham (UK), Sirra Njai (The Gambia), Johnson Nkem (Cameroon), Jane Mukarugwiza Olwoch (South Africa), Pieter Pauw (Netherlands), Emilia Pramova (Bulgaria), Clionadh Raleigh (Ireland), Debra Roberts (South Africa), Carla Roncoli (USA), Aissa Toure Sarr (Senegal), Michael Henry Schleyer (South Africa), Lena Schulte-Uebbing (Germany), Roland Schulze (South Africa), Hussen Seid (Ethiopia), Sheona Shackleton (South Africa), Mxolisi Shongwe (Swaziland), Daithi Stone (Canada / South Africa), David Thomas (UK), Okoro Ugochukwu (Nigeria), Dike Victor (Nigeria), Katharine Vincent (South Africa), Koko Warner (Germany), Sidat Yaffa (The Gambia)

Review Editors
Pauline Dube (Botswana), Neil Leary (USA)

Volunteer Chapter Scientist
Lena Schulte-Uebbing (Germany)

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Frequently Asked Questions
22.1: What is the significance of migration in the context of climate change adaptation in Africa?

22.2: How could climate change impact food security in Africa?
22.3: What role does climate change play with regard to violent conflict in Africa?

References

Executive Summary

Evidence of warming over land areas, consistent with anthropogenic climate change, has increased (*high confidence*). Decadal analyses of temperatures strongly point to an increased warming trend across the continent. In addition, changes in the seasonality and amount of precipitation have also been observed in sub-regions of Africa that include reduced long rains over parts of Eastern Africa and reduced summer precipitation over parts of Southern Africa. [22.2.1.1, 22.2.2.1]

Temperature rise by the end of this century are likely to exceed a 2° C threshold (*medium confidence*). Warming projections under medium and high Representative Concentrations Pathways (RCP) for GHG emissions indicate that extensive areas of Africa (medium RCP) and all of Africa (high RCP) will exceed 2° C by the last two decades of this century. Under a high RCP, that exceedence could occur by mid-century across much of Africa. [22.2.1.2, 22.2.2.2]

Attainment of the Millennium Development Goals (MDGs) in Africa would strengthen the region's resilience to various external shocks, including climate change. Vital links exist between climate change and the MDGs in Africa. On one hand climate change may adversely affect progress toward reaching the MDGs, while slow development can exacerbate the effects of climate change in the region (*confidence level to be added*). [22.3.1]

Africa as a whole has made significant progress on a number of MDGs, including education and gender equality and empowerment of women. However, slower progress has been made on MDGs such as the eradication of extreme poverty and hunger, and improvements in health and environment such as an increase in sanitation and basic housing facilities for poor populations including people living in slums. Moreover, progress toward the MDGs conceals high levels of spatial and group disparities, as improvement in development indicators is skewed in favor of higher-income groups and urban populations (*high confidence*). [22.3.1]

The impacts of climate change, mainly through sea level rise, combined with other extreme events (such as high tide levels and high storm swells) have the potential to threaten coastal zones, particularly coastal towns (*high confidence*). The example of the Kwa Zulu Natal coast (South Africa), where Durban is located, which was damaged by a combination of high water level and high storm swell in March 2007, is indicative of what could happen. **Evidence is growing that the costs of these impacts will increase for economic sectors and people living in these zones (medium confidence). [22.3.2.3.1, 22.3.7]**

Ocean ecosystems, in particular coral reefs, will be affected by climate change-induced ocean acidification as well as changes in upwelling, thus affecting crucial economic activities (mainly fisheries; *medium confidence*). [22.3.2.3.2, 22.3.4.4]

The impact of climate change on water availability in Africa is uncertain (*high confidence*). Water resources are subjected to high hydro-climatic variability over space and time, and are a key constraint on the continent's continued economic development. Water is the primary medium through which early and subsequent climate change impacts will be felt by people, ecosystems, and economies. Many of the fragile terrestrial and aquatic ecosystems in Africa are implicitly or explicitly water-dependent. The impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical socio-political and economic footprint. Strategies and plans of action to adapt to climate change through an integrated approach to land and water management are urgently needed to establish effective resilience to the projected impacts of climate change. [22.3.2.2, 22.3.3]

Progress is being achieved on managing risks to food production from current climate variability but these will likely not be sufficient to address long-term risks from climate change (*high confidence*). Livelihood-based approaches for managing risks to food production from multiple stressors, including rainfall variability, have increased substantially in Africa since the IPCC's Fourth Assessment Report (AR4). While these efforts can improve the resiliency of agricultural systems in Africa over the near term, these adaptations are likely to be insufficient for coping with risks from long-term climate change, which will be variable across regions and farming system types. Nonetheless, processes such as collaborative, participatory research that includes scientists and farmers, strengthening of communication systems for anticipating and responding to climate risks, and increased flexibility in livelihood options, which serve to strengthen coping strategies in agriculture for near-term risks from climate variability, provide potential pathways for adaptive capacities for climate change. [22.4.5.4, 22.4.5.7, 22.4.6, 22.6.1]

Recent evidence further strengthens a key finding from the AR4 that "agricultural production and food security (including access to food) in many African countries and regions are likely to be severely compromised by climate change and climate variability" (*high confidence*). Temperature rise and a reduction in growing season length by mid-century are very likely to significantly reduce crop productivity with strong adverse effects on food security. New evidence is also emerging that fisheries and high-value perennial crops could also be adversely affected by temperature rise, and that the pressure of pests and diseases on crops and livestock is expected to increase as a result of climate change and other factors. Moreover, new challenges to food security are emerging as a result of strong urbanization trends on the continent and increasingly globalized food chains, which require better understanding of the multi-stressor context of food and livelihood security in Africa. [22.3.4]

Evidence is growing that climate change is likely to increase the burden of a wider range of health outcomes (*high agreement, medium confidence*). Findings on malaria are similar to the AR4, emphasizing the spatial and temporal spread of malaria in the East Africa Highlands and increased transmission intensity in South Africa. Leishmaniasis incidence in North Africa has been found to have a significant positive relation with rainfall pattern and changes in the frequency of epidemics and spatial spread to urban areas and to sub-Saharan Africa. Indirectly, climate change could increase the burden of malnutrition, which will have the highest toll on children and women. **Climate change is a multiplier of existing vulnerability to health outcomes (*high confidence*) including inadequate water and sanitation coverage, food security, and access to health care and education.** Improvements in these existing vulnerabilities will decrease the impacts of climate change on health. [22.3.5]

In all regions of the continent, national governments are initiating governance systems for adaptation and responding to climate change (*medium evidence, high agreement*). Some progress has been made on national and sub-national policies and strategies beyond the initial National Adaptation Programmes of Action, and on mainstreaming adaptation into sectoral planning, for example in the health sector. **Institutional frameworks cannot yet effectively coordinate the range of adaptation initiatives being implemented, resulting in a largely ad hoc and project-level approach, which is often donor-driven and may not result in local or national ownership (*medium agreement, medium evidence*).** While institutions for collaborative governance are developing, a separation remains between policy formulation and vulnerable people adapting autonomously on the ground, exacerbated by low levels of capacity in local governments to deal with complex socio-ecological change. National policies are often at odds with autonomous local adaptation strategies, which can act as a barrier to adaptation, especially where cultural, traditional and context-specific factors are ignored (*high confidence*). [22.4.4]

While a wide range of adaptation options, approaches, and decision tools are being tested and implemented at different scales across Africa, these have not yet been taken to a scale that would address the complex vulnerabilities and needs identified (*medium evidence, high agreement*). Efforts such as disaster risk reduction, social protection, adaptation technologies, climate-resilient infrastructure, ecosystem restoration, and livelihood diversification are reducing vulnerability and enhancing resilience, but this is still largely confined to local scales and isolated initiatives. Ecosystem-based approaches and pro-poor integrated adaptation-mitigation initiatives hold promise for a more coherent approach to adaptation; and emphasis on highly vulnerable groups such as children and an enhanced policy environment for community-based adaptation can promote equity goals. **Coastal adaptation has the potential to considerably reduce projected impacts in the coastal zones (*high confidence*).** Adaptation

in the health sector will build on existing public health interventions as well as specific adaptation measures such as early warning systems. [22.4.5]

In addition to technological and infrastructural approaches, evidence has increased of the importance of 'soft path' options and flexible and iterative learning approaches for effective adaptation (*medium evidence, medium agreement*). 'Soft' measures include harnessing ecosystem services for climate proofing, such as coastal afforestation and catchment restoration. Learning approaches being explored include action research, participatory adaptation planning, and adaptive management, and may involve co-production of knowledge – such as combining local and traditional knowledge with science, and conflict resolution. Attention to the cultural, ethical, and rights considerations of adaptation has also increased. [22.4.5]

The inadequacy of developmental strategies to counter current climate risks reinforces the need for strong inter-linkages between adaptation and development, and for low-regrets adaptation strategies that produce developmental co-benefits (*high confidence*). [22.4.3]

Growing understanding of the multiple interlinked constraints on increasing adaptive capacity is beginning to indicate potential limits to adaptation in Africa (*limited evidence, high agreement*). Climate change combined with other external changes (environmental, social, political, technological) may overwhelm the ability of people to cope and adapt, especially if the root causes of poverty and vulnerability are not addressed. The risks of maladaptation are increased by development interventions that often fail to consider how different types of change interact and undermine the ability of people to cope with multiple stressors. Evidence is growing for the effectiveness of flexible and diverse development systems that are designed for reducing vulnerability, spreading risk, and building adaptive capacity. These points indicate the need for new development trajectories that place climate resilience, ecosystem stability, equity and justice at the centre of development efforts. [22.4.6]

Human security of people in Africa will increasingly be threatened by the impacts of climate variability (*high agreement, medium* to *robust evidence*). Food and health insecurity, migration and displacement, and violent conflict are particular areas of concern for the African continent. The impacts of climate change have the potential to increase food insecurity and distributional conflicts. Evidence is growing that displacement and migration patterns due to climate change-related drivers will be subject to substantial shifts. **The degree of adaptation will be decisive with regard to the risks related to human security in Africa**. Based on the multi-model CMIP5 analysis, which indicates that temperature rise will exceed a 2ºC threshold across Africa by the middle to end of this century, the risks for human security will be high to very high by 2080-2100 and medium to high by 2030-2040. [22.3.6]

Institutional capacities and governance mechanisms need to be strengthened with respect to the ability of national governments and scientific institutions in Africa to absorb and effectively manage large amounts of funds allocated for adaptation, in order that the effectiveness of adaptation initiatives is assured (*medium confidence*). Indigenous and rural poor communities in remote locations, the urban poor living in precarious settlements, and displaced persons, especially women and children, are those most adversely affected by climate change while they are actually meant to be the main beneficiaries of adaptive action. It is therefore imperative that strong institutional capacity to manage climate finance funds be made a priority. The potential for ineffective and mismanaged climate finance funds are – among other reasons – rooted in the level of complexity, uncertainty, and novelty that surrounds many climate issues. [22.4.4.3, 22.6.2]

22.1. Introduction

22.1.1. Structure of the Regions

The African continent (including Madagascar) is the world's second largest and most populous continent (1 billion in 2009, representing 14.7% of the world's population) behind Asia. It is composed of 55 countries (of which 5 are small island states) of which 33 belong to the Least Developed Countries (LDCs). The continent is organized at the regional level under the African Union (AU).[1] The AU's Assembly of Heads of State and Government has officially recognized eight Regional Economic Communities (RECs) (Ruppel, 2009; Nwauche, 2009). Except for the Sahrawi

Arab Democratic Republic,[2] all AU member states are affiliated with one or more of these RECs. These RECs include the Arab Maghreb Union (AMU), with 5 countries in Northern Africa; the Community of Sahel-Saharan States (CEN-SAD), grouping 25 countries; the Common Market for Eastern and Southern Africa (COMESA), grouping 19 countries in Eastern and Southern Africa; the East African Community (EAC), with 5 countries; the Economic Community of Central African States (ECCAS), with 10 countries; the Economic Community of West African States (ECOWAS), with 15 countries; the Intergovernmental Authority on Development (IGAD); and the Southern African Development Community (SADC), with 15 countries. The regional subdivision of African countries into REC's is a structure used by the AU and the NEPAD (New Partnership for Africa).

[FOOTNOTE 1: Due to the controversies regarding the Sahrawi Arab Democratic Republic, Morocco withdrew from the Organization of African Unity (OAU) in protest in 1984 and, since South Africa's admittance in 1994, remains the only African nation not within what is now the AU.]

[FOOTNOTE 2: Although the Sahrawi Arab Democratic Republic has been a full member of the OAU since 1984 and remains a member of the AU, the republic is not generally recognized as a sovereign state. While most African states have recognized the republic (e.g., Namibia and South Africa), several others have withdrawn their former recognition (e.g., Cape Verde, the Seychelles), and some have temporarily frozen diplomatic relations (e.g., Costa Rica, Ghana), pending the outcome of a respective United Nations (UN) referendum that would allow the people of Western Sahara to decide the territory's future status. The republic has no representation in the UN.]

22.1.2. Major Conclusions from Previous Assessments

22.1.2.1. Regional Special Report and Assessment Reports 1 – 4 / Chapter 9

The first evaluation of the potential impacts of climate change in Africa was done for the IPCC special report on regional climate change (Zinyowera *et al.*, 1997). This report presented mainly the sensitivity of water resources and coastal zones to some climatic parameters. Since the report was published, climate change was considered as an additional burden on an already stressful situation. Lack of data on energy sources, the uncertainties linked to the climate change scenarios (mainly for precipitation), the need for a better integration of studies, and the necessary links between science and decisionmakers were underlined as major challenges for Africa. In the Third Assessment Report, specific chapters were dedicated to regions, Africa being one (Desanker *et al.*, 2001). In the third report, the main focus is on the potential impacts of climate change and vulnerability for the six sectors considered (water resources, food security, natural resources and biodiversity management, health, human settlements and infrastructure, and desertification). Literature on adaptation strategies was included in the assessment for each of these sectors. That desertification was considered as a sector expressed the threats of desertification and droughts to the economy of the continent. Globally, most of the adaptation options suggested were linked with better management of the different resources. The main gaps and needs, such as capacity building, data needs, and the development of integrated analysis, as well as the consideration of other languages, were identified. The Fourth Assessment Report (AR4) confirmed that the vulnerability of the continent was mainly due to its low adaptive capacity (Boko *et al.*, 2007). It considered the different sources of vulnerability, encompassing socioeconomic causes (demographic growth, governance, conflicts, etc.) and examined the impacts of climate change on various sectors (energy, tourism and coastal zones are considered separately). The potential impacts of extreme weather events (droughts and floods) were also considered in AR4. The question of adaptation costs was raised, as well as the need for mainstreaming climate change adaptation into national development policies. Two case studies were analyzed, on food security and traditional knowledge. The first emphasized that climate change could affect the three main components of food security while the second case study illustrated that African communities have prior experience with climate variability, although this knowledge will be sufficient to face climate change impacts. A list of needs was also identified regarding future studies: better knowledge of climate variability; more studies on the impacts of climate change on water resources, energy, biodiversity, tourism, and health; the links between different sectors (e.g., between agriculture, land availability, and biofuels); developing links with the disaster reduction community; increasing interdisciplinary analysis of climate change; and strengthening institutional capacities.

22.1.2.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

Due to the high vulnerability of the African continent to the negative effects of climate change, the Special Report of the IPCC on managing the risks of extreme events and disasters to advance climate change adaptation (IPCC, 2012) is of particular relevance. According to the report, confidence in observed trends in daily temperature extremes in Africa generally varies from *low* to *medium* depending on the region (Seneviratne *et al*., 2012). In southern Africa, there is *medium confidence* that droughts will intensify in the 21st century in some seasons, due to reduced precipitation and/or increased evapotranspiration (Seneviratne *et al*., 2012).

22.2. Observed Climate Trends and Future Projections

22.2.1. Temperature

22.2.1.1. Observed Trends

Over the last 100 years Africa's temperature has increased by 0.5°C (Desanker *et al*., 2001; Clark, 2006; Kniveton *et al*., 2009; Mohamed, 2011; Grab and Craparo, 2011; Hoffman *et al*., 2011). Near-surface air temperature anomalies in Africa were significantly higher for the period 1995–2010 compared to the period 1979–1994 (Collins, 2011). Over West Africa, warming is likely due to natural variability or human activity, rather than a result of variations in the El Niño-Southern Oscillation. Min and Hense (2007) found strong evidence of an anthropogenic signal in continent-wide temperature increases in the 20th century. Over most regions of Africa, such a signal appears in the frequency of unusually hot seasons (Stott *et al*., 2011) and the increase in the number of droughts occurring in the Sahel since 1970 is well documented (Greene *et al*., 2009).

Anyah and Qiu (2012) indicate that both equatorial and southern parts of the eastern Africa region have been experiencing a significant increase in temperature since the beginning of the early 1980s. Similarly, recent reports from the Famine Early Warning Systems Network (FEWS NET) indicate that there has been an increase in seasonal mean temperature over time in many areas of Ethiopia, Kenya, South Sudan, and Uganda (Funk *et al*., 2011; Funk *et al*., 2012). In addition, warming of the surface temperature and an increase in the frequency of extreme warm events has been observed for countries bordering the western Indian Ocean between 1961 and 2008 (Vincent *et al*., 2011).

In recent decades, most of southern Africa has also experienced upward trends in annual mean, maximum, and minimum temperature over large extents of the subregion during the last half of the 20th century, with the most significant warming occurring during the last two decades (Zhou *et al*., 2010; Collins, 2011; Kruger and Sekele, 2012). Minimum temperatures have increased more rapidly relative to maximum temperatures, which has decreased the diurnal temperature range over inland southern Africa (New *et al*., 2006) is influenced by decreases in surface solar heating (Zhou *et al*., 2010). A reduction in cold night occurrences is consistent with an increase in minimum temperatures (Kruger and Sekele, 2012).

22.2.1.2. Projected Trends

James and Washington (2012) find that in the context of a 1°C to 4°C global temperature increase by the end of the century, temperatures in Africa are projected to rise more than the global average, particularly in the more arid regions. Coupled Model Intercomparison Project phase 3 (CMIP 3) models, in the A1B middle-of-the-road scenario indicate that by the end of the 21st century, summer temperatures in the Sahel will be higher than any in recorded history (Battisti and Naylor, 2009; Biasutti and Sobel, 2009). Oguntunde and Abiodun (2013) project a drier climate during the rainy season and a wetter climate during the dry season between 2030 and 2050, and a warmer climate over the Niger River basin (NRB) in all months.

Climate model projections from the IPCC Special Report: Emissions Scenarios (SRES) A2 and B1 emissions scenarios over Ethiopia show warming in all four seasons across the country, which may cause a higher frequency of

heat waves as well as higher rates of evaporation (Conway and Schipper, 2011). Projected minimum temperatures over equatorial eastern Africa are more than 2°C higher than the 1981–2000 average by the middle and end of the 21st century (Anyah and Qiu, 2012). Elshamy et al. (2009) projected a temperature increase over the upper Blue Nile of between 2°C and 5°C at the end of the century.

Mean warming in Southern Africa is projected to exceed global warming in all seasons (Sillmann and Roeckner, 2008; Watterson, 2009; Mariotti *et al.*, 2011; James and Washington, 2012; Orlowsky and Seneviratne, 2012). Furthermore, towards the end of the 21st century, the projected warming, which is greater than 4ºC under the highest radiative forcing, far exceeds natural climate variability (Moise and Hudson, 2008). Higher warming rates are evident over the semi-arid southwestern parts of the subregion covering northwestern South Africa, Botswana, and Namibia. These areas are thus projected to become even drier in the future climate (Moise and Hudson, 2008; Engelbrecht *et al.*, 2009; Watterson, 2009; Shongwe *et al.*, 2009). Accelerated warming is consistent with reduced surface evaporative cooling. Observed and simulated variations in past and projected future annual average temperature over five African regions (UMA, SADC, ECCAS, ECOWAS, SADC and COMESA) are captured in Figure 22-2. Multi-model CMIP5 analysis indicates that temperature rise will exceed a 2°C threshold across Africa by the middle to end of this century (Figure 22-1).

[INSERT FIGURE 22-1 HERE
Figure 22-1: Observed and simulated variations in past and projected future annual average precipitation and temperature. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

[INSERT FIGURE 22-2 HERE
Figure 22-2: Observed and simulated variations in past and projected future annual average precipitation and temperature over five African regions (Arab Maghreb Union- AMU, Common Market for Eastern and Southern Africa – COMSEA, Southern African Development Community – SADC, Economic Community of West African States – ECOWAS, Economic Community of Central African States – ECCAS). Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3. The regions are described in 22.1.2, but COMESA-north covers COMESA north and inclusive of Rwanda, Uganda, and Kenya. Precipitation is included for land territories only, while temperature is included for both land and exclusive economic zone territories.]

22.2.2. Precipitation

22.2.2.1. Observed Changes

At the beginning of the 21st century, Sahel rainfall was recorded as being moderately stable around the 1961–1990 average of 371 mm, although this period was about 25% drier than earlier decades of the 20th century. Recent

studies of rainfall trends across the Sahel confirm a decrease in rainfall associated with a decrease in the number of rainy days (Mohamed, 2011). Observations of the Guinea coast reveal a clear depreciation of the length of the rainfall break in August that defines the bimodal nature of the wet season in the southern part of Nigeria. The two- to three-week period of temporary rainfall cessation is gradually declining into a relatively insignificant two- to three-day break (Chineke *et al*., 2010).

Precipitation in eastern Africa shows a high degree of spatial variability dominated by a variety of physical processes (Hession and Moore, 2011). Williams and Funk (2010) and Funk et al. (2008) indicate that over the last three decades rainfall has decreased over eastern Africa during the 'long-rains' season, which usually lasts from March to May/June. The suggested physical link to the decrease in rainfall is the rapid warming of Indian Ocean sea surface temperature (SST), which causes an increase in convection and precipitation over the tropical Indian Ocean and thus contributes to increased subsidence over eastern Africa and a decrease in rainfall during March to May/June (Funk *et al*., 2008; Williams and Funk, 2010). Similarly, Lyon and DeWitt (2012) show a decline in the March–May seasonal rainfall over eastern Africa, with particular attention to the abrupt decline of precipitation during the long-rains of 2011. Summer (June–September) monsoonal precipitation has declined substantially throughout much of the Great Horn of Africa over the last 60 years (during the 1948–2009 period; Williams *et al*., (2012)) as a result of the changing sea level pressure (SLP) gradient between Sudan and the southern coast of the Mediterranean Sea and the southern tropical Indian Ocean region (Williams *et al*., 2012). These results are contrary to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (AR4) findings, which indicate a precipitation increase over eastern Africa (Christensen *et al*., 2007). Lyon and DeWitt (2012) conclude that recent east African precipitation trends differ from projected climate model trends because recent cooling in the eastern equatorial Pacific offsets the equatorial Pacific SST warming that is projected by CMIP3 Global Circulation Models (GCMs) in future scenarios.

During the second half of the 20th century, a 20% reduction in late summer precipitation as well as increased aridity has been reported over the western parts of southern Africa, extending from Namibia, through Angola, and toward the Congo (Hoerling *et al*., 2006). The drying is associated with an upward trend in tropical Indian Ocean SSTs. Modest downward trends are found along Botswana, Zimbabwe, and western South Africa. Apart from changes in total or mean summer rainfall, certain intra-seasonal characteristics of seasonal rainfall such as onset, duration, dry spell frequencies, and rainfall intensity as well as delay of rainfall onset have changed (Tadross *et al*., 2005; Thomas *et al*., 2007; Tadross *et al*., 2009; Kniveton *et al*., 2009). An increasing trend in daily rainfall intensity is compensating for the increase in the frequency of dry spells (New *et al*., 2006).

22.2.2.2. Projected Changes

Precipitation projections show high inter-model variation in both the amplitude and direction of change, but in all models precipitation changes are enhanced as global temperatures increase, and the degree of response is regionally specific. Paeth and Thamm (2007) report that until 2025 a considerable reduction in precipitation over most of tropical Africa can be expected. The reduction will amount to more than 20 to 40% of the annual total and be most concentrated in the Congo Basin and the Sahel. Diallo et al. (2012) and Caminade and Terray (2010) report that the western Sahel will undergo substantial drying in the future mostly due to a decrease in peak monsoon rainfall. Projected midsummer drought over the Guinean Coast region is partly related to a weakened monsoon flow, which is a function of SST gradients (Patricola and Cook, 2010a).

Shongwe et al. (2011) suggest that there will be a wetter climate with more intense wet seasons and less severe droughts over eastern Africa during October November December (OND) and March April May (MAM) seasons, with some uncertainty about the rate of change. Patricola and Cook (2010b) predict severe drying over most parts of Uganda, Kenya, and South Sudan in August and September by the end of the 21st century as a result of a weakening Somali jet and Indian monsoon. Climate model projections over Ethiopia indicate a wide range of rainfall spatial pattern changes (Conway and Schipper, 2011). As indicated by Elshamy et al. (2009) GCMs do not agree on the direction of precipitation change in the upper Blue Nile basin between 2080 and 2098.

Precipitation projections exhibit higher spatial and seasonal dependence than temperature scenarios (Orlowsky and Seneviratne, 2012). In the annual mean, models show a dry signal over the climatologically dry southwest, extending northeastward from the desert areas in Namibia and Botswana (Moise and Hudson, 2008; Engelbrecht *et al.*, 2009; James and Washington, 2012; Orlowsky and Seneviratne, 2012). During the austral summer months, dry conditions are projected in the southwest while wetter conditions, within natural climate variability (Moise and Hudson, 2008), are projected in the southeast of South Africa (Hewitson and Crane, 2006; Engelbrecht *et al.*, 2009). Consistent with the AR4, drier winters are projected over a large area in southern Africa as a result of the poleward displacement of mid-latitude storm tracks (Moise and Hudson, 2008; Engelbrecht *et al.*, 2009; Shongwe *et al.*, 2009; Seth *et al.*, 2011; James and Washington, 2012). Rainfall decreases are also projected during austral spring months, implying a delay in the onset of seasonal rains over a large part of the summer rainfall region of Southern Africa (Shongwe *et al.*, 2009; Seth *et al.*, 2011). The sign, magnitude, and spatial extent of projected precipitation changes are dependent on the coupled general circulation model (CGCM) employed, due primarily to parameterization schemes used and their interaction with model dynamics (Hewitson and Crane, 2006; Rocha *et al.*, 2008). However, CGCMs do converge on their synoptic-scale circulation response to radiative forcing which, when downscaled, project that the eastern parts of South Africa will become wetter toward the end of the 21st century (Hewitson and Crane, 2006). Multi-model CMIP5 analysis indicates the potential for wide-scale changes in precipitation across Africa by the middle to end of this century (Figure 22-1). Observed and simulated variations in past and projected future annual average precipitation over five African regions (UMA, ECCAS, ECOWAS, SADC and COMESA) are captured in Figure 22-2.

22.2.3. Extreme Events

Climate extremes such as droughts and floods, which are aggravated by climate change and variability, are being experienced more frequently over eastern Africa (Funk *et al.*, 2008; Williams and Funk, 2010; Shongwe *et al.*, 2011; Lyon and Dewitt, 2012). Recent research has suggested that continued warming in the Indian–Pacific warm pool is likely to contribute to more frequent East African droughts, such as the 2011 drought, during the spring and summer seasons.

An increase in warm extremes and a decrease in cold extremes in recent decades is consistent with the general warming trend over southern Africa (New *et al.*, 2006; Tebaldi *et al.*, 2006; Kruger and Sekele, 2012). The probability of austral summer heat waves over South Africa increased over the last two decades of the 20th century compared to 1961 to 1980 (Lyon, 2009). Enhanced heat wave probabilities are associated with deficient rainfall conditions that tend to occur during El Niño events.

Future projections indicate that all heat wave indices and warm spell durations will increase, suggesting an increased persistence of hot days toward the end of the century (Tebaldi *et al.*, 2006; Orlowsky and Seneviratne, 2012). An increase in sensible heat flux relative to latent heat flux is related to this, a condition favorable for a higher frequency and/or intensity of heat waves (Lyon, 2009). Future precipitation projections demonstrate changes in the scale of the rainfall probability distribution, indicating that extremes of both signs will become more likely in the future (Kay and Washington, 2008). The southwestern regions are projected to be at a high risk of severe droughts during the 21st century and beyond (Hoerling *et al.*, 2006; Shongwe *et al.*, 2011). Intense floods are projected over northern Mozambique, Malawi, and southern Tanzania. Large uncertainties surround likely changes in tropical cyclone landfall from the southwest Indian Ocean that have resulted in intense floods during the 20th century.

22.3. Vulnerability and Impacts

This section highlights how Africa is vulnerable (since the main drivers of vulnerability have not changed since AR4) and the main observed and potential impacts of climate change on natural resources and ecosystems, as well as on different economic sectors. Figure 22-3 summarizes the main conclusions regarding observed changes in regional climate and their relation to anthropogenic climate change (described in 22.2) as well as regarding observed changes in natural and human systems and their relation to observed regional climate change (described in this section). Detection and attribution of anthropogenically-driven climate change is highest for temperature measures.

In many regions, evidence is constrained by limited monitoring. However, impacts of observed precipitation changes are amongst the observed impacts with the highest assessment of confidence, implying that some of the potentially more significant impacts of anthropogenic climate change for Africa are of a nature that challenges detection and attribution analysis (18.5.1).

[INSERT FIGURE 22-3 HERE
Figure 22-3: Summary of detection and attribution assessments of the relation of observed climate change over Africa with anthropogenic emissions (left) and of the relation of observed changes in natural and human systems with observed regional climate changes (right). All detection assessments are against a no-change reference and all attribution assessments for a major role of anthropogenic emissions (left) or observed regional climate change (right), except for "change in disease incidence" for which the detection assessment is relative to what would have been expected based on changes in livelihoods and health care and for which the attribution assessment is for a minor role of climate change in disease incidence. COMESA-n covers the half of COMESA north of and including Rwanda, Uganda, and Kenya. Discussion of these assessments are in 22.2, 22.3, 22.5.1, WGI AR5 Chapter 10, SREX 3.3, SREX 3.5, and 18.5.1. The detection and attribution assessments follow the specifications described in 18.2.]

22.3.1. Socioeconomic and Environmental Context

Socioeconomic development in Africa may strengthen its resilience to various external shocks, including climate change. In 2009, the Human Rights Council adopted Resolution 10/4[3] which noted the effects of climate change on the enjoyment of human rights, and reaffirmed the potential of human rights obligations and commitments to inform and strengthen international and national policy making.

[FOOTNOTE 3: U.N. Doc. A/HRC/10/L.11.]

The impacts of climate change on human rights have been explicitly recognised by the African Commission on Human and Peoples' Rights (hereafter African Commission) in its Resolution on Climate Change and Human Rights and the Need to Study its Impact in Africa (ACHPR/Res 153 XLV09). The 1981 African (Banjul) Charter on Human and Peoples' Rights (hereafter African Charter) protects the right of peoples to a 'general satisfactory environment favorable to their development' (Article 24). The recognition of this right and the progressive jurisprudence by the African Commission in environmental matters underline the relevance and linkage between climate change and human rights (Ruppel, 2012). Strong links exist between climate change and the MDGs: climate change may adversely affect progress toward attaining the MDGs, while slow progress in attaining most MDGs has a negative impact on the resilience and adaptive capabilities of African individuals, communities, states, and nations and consequently decreases their adaptive capacity to climate change.

The African continent has managed to make significant progress on some MDGs but not all. Aggregate trends in Africa's progress toward the MDGs conceal high levels of spatial and group disparities, and progress on all indicators is skewed in favor of higher-income groups and urban populations, which means further marginalization of already excluded groups (United Nations *et al*., 2008; African Development Bank *et al*., 2010; World Bank and International Monetary Fund, 2010). As a whole, the continent is experiencing a number of demographic and economic constraints (Muchena *et al*., 2005; Fermont *et al*., 2008). The population of the continent has more than doubled since 1980; exceeding one billion in 2011 and expected to reach 2.9 billion by the year 2050 if fertility were to remain constant (United Nations Department of Economic and Social Affairs, 2011). The global economic crisis is adding other constraints on economic development efforts resulting in increased loss of livelihood and widespread poverty (Moyo, 2009; Easterly, 2009; Adesina, 2010). The percent of the population below the poverty line has decreased from 56.5% in 1990 to 47.5% in 2008 (excluding North Africa), however a significant proportion of the population living below the poverty line remains chronically poor (Economic Commission for Africa *et al*., 2012). And although poverty in rural areas has declined from 64.9% in 1998 to 61.6% in 2008, it is still double the prevailing average in developing countries in other regions (IFAD, 2010).

African agriculture, which is the main economic activity in terms of employment share, is 95% rain fed (UNEP, 2008). Stagnant agricultural yields, relative to the region's population growth, have led to a fall in per capita food availability since the 1970s (United Nations *et al*., (2008); Figure 22-4).[4] In addition, the recent rise in global food prices aggravates food insecurity among the poor, increasing the risk of malnutrition and its consequences (United Nations *et al*., 2008). For example, it was estimated that the global rise in food prices has contributed to the deaths of an additional 30,000 to 50,000 children suffering from malnutrition in 2009 in sub-Saharan Africa (Friedman and Schady, 2009; UNSCN, 2009; World Bank and International Monetary Fund, 2010; UNDP *et al*., 2011). This situation may be complicated further by changes in rain variability and extreme weather events affecting the agriculture sector (Yabi and Afouda, 2012).

[INSERT FIGURE 22-4 HERE
Figure 22-4: Number of undernourished people in Africa between 1994/1996 and 2010/2012
Source: www.fao.org/fileadmin/templates/ess/foodsecurity/Food_Security_Indicators.Xlsx.]

[FOOTNOTE 4: Lack of extension services for farmers in Africa can also prevent the utilization and spread of innovations and technologies that can help mitigate climate change.]

Africa has made much progress in the achievement of universal primary education, however, the results are unevenly distributed. The net enrollment rate in primary education has increased from 65% in 1999 to 83% in 2008, with an 18% improvement in sub-Saharan Africa. Nevertheless, a considerable number of children, especially girls from poor backgrounds and rural communities, still do not have access to primary education (United Nations *et al*., 2008). From the livelihood perspective, African women are vulnerable to the impacts of climate change because they shoulder an enormous but imprecisely recorded portion of the responsibility for subsistence agriculture (Viatte *et al*., 2009).[5] Global financial crises, such as the one experienced in 2007/2008, may cause job losses in the formal sector and men may compete for jobs in the informal sector that were previously undertaken by women, making them more vulnerable (African Development Bank *et al*., 2010).

[FOOTNOTE 5: For instance, more than 84% of women in sub-Saharan Africa, compared with 71% of men, are engaged in such jobs. In Northern Africa, even though informal or self-employment is less predominant, the gender gap is stark, with almost twice as high a proportion of women as men in the more vulnerable informal and self-employed status (53% of women compared with 28% of men) (UN DESA, 2010).]

Efforts to combat AIDS, tuberculosis, and malaria under the MDGs have led to progress in preventing and treating these diseases (African Development Bank *et al*., 2010), however, malaria is still endemic in most African countries and represents a major cause of morbidity and mortality.

Deforestation in Africa over the periods 1990–2000 and 2000–2010 has affected 4.1 and 3.7% of total forest area, respectively (UNDP *et al*., 2011). The rich biodiversity of the forests remains endangered by the high rate of deforestation and forest degradation as well as a decline in primary forests. Monitoring of biodiversity is weak in Africa, such that almost 50% of medicinal plants surveyed in 2009 – used by 80% of the population – faced extinction (UNEP, 2012).

Significant efforts have been made to improve access to safe drinking water and sanitation in Africa, with access to safe drinking water increasing from 56 to 65% between 1990 and 2008, with sub-Saharan Africa nearly doubling the number of people using an improved drinking water source – from 252 to 492 million over the same period. Despite such progress, significant disparities in access to safe water and sanitation, between not only urban and rural but also between large- and medium- and small-sized cities, still exist (UNDP *et al*., 2011). Use of improved sanitation facilities, meanwhile, is generally low in Africa, reaching to 41% in 2010 compared to 36% in 1990 (UNDP *et al*., 2011).

22.3.2. Ecosystems

Regarding the vulnerability and impacts of climate change on ecosystems, it is recognized that interactions between the different drivers of ecosystems behavior are complex, which makes the prediction of the impacts of climate change more difficult (see Chapter 4). In AR4, the chapter on Africa indicated that extensive pressure is exerted on different ecosystems by human activities (deforestation, forest degradation, biomass for energy) as well as processes inducing changes like fires or desertification. Even if the trend is toward better preservation of ecosystems and a decrease in degradation (like deforestation), pressures linked, for example, to agriculture and food security, energy demand, and urbanization are increasing, putting these ecosystems at risk. This chapter emphasizes a few findings regarding the vulnerability and impacts of these ecosystems, including terrestrial, freshwater, and coastal/ocean systems.

22.3.2.1. Terrestrial Ecosystems

A shift in the geographic location or extent of a biome can signal a substantial change in climate and fundamentally alter habitats and the provision of ecosystem services to people. While field research has detected numerous elevation and latitudinal shifts in biomes around the world attributable to climate change more than to human land use change (Gonzalez *et al*., 2010), only a few efforts have examined biome shifts in Africa. At sites across West and Central Africa, field research on tree species distributions from 1960 to 2000 detected a southward shift of three biomes: tropical savanna (Sahel), tropical woodland (Sudan), and tropical deciduous forest (Guinea) – and attributed the shift to anthropogenic climate change (Gonzalez *et al*., 2012). Field data from Burkina Faso also suggest possible southward biome shifts of the Sahel and Sudan consistent with, but not formally attributed to, climate change (Wezel and Lykke, 2006; Maranz, 2009). Land use change may be a factor in the Burkina Faso sites.

A number of studies indicate that precipitation is the primary factor determining tree cover in African savannas, woodlands, and forests (Bucini and Hanan, 2007; Sankaran *et al*., 2008; Good and Caylor, 2011; Greve *et al*., 2011). Disturbances that substantially modify the climatic limits of biomes include fire, grazing, agricultural cultivation, and timber harvesting (Bucini and Hanan, 2007; Sankaran *et al*., 2008; Ahrends *et al*., 2010; Ellis *et al*., 2010; Groen *et al*., 2011; Staver *et al*., 2011; Favier *et al*., 2012).

Projected changes in precipitation and disturbance under climate change may substantially alter the nduextent and locations of biomes. Projections of potential future vegetation indicate the wide vulnerability of ecosystems in Africa to future biome shifts. A set of dynamic global vegetation models (DGVMs) and one equilibrium model project biome changes over 5 to 10% of the land in Africa from around 1990 to 2100 for a range of the Coupled Model Intercomparison Project phase three (CMIP3) general circulation model (GCM) runs of the IPCC Special Report on Emissions Scenarios (SRES) emissions scenarios (Hély *et al*., 2006; Scholze *et al*., 2006; Alo and Wang, 2008; Delire *et al*., 2008; Sitch *et al*., 2008; Scheiter and Higgins, 2009; Gonzalez *et al*., 2010; Bergengren *et al*., 2011). An analysis of the vulnerability of ecosystems to biome shifts that combined 1901–2002 historical climate change and 1990–2100 DGVM projections estimated that 12% of African land area is highly to very highly vulnerable to biome shifts and that over 100 million people live in those areas (Gonzalez *et al*., 2010) (Figure 22-5). An equilibrium vegetation model analysis for West Africa estimated that, under the A2 emissions scenario, some 10 to 50% of the land in Africa is vulnerable to biome shifts (Heubes *et al*., 2011). Projections generally agree on latitudinal shifts in vegetation, degradation of tropical biomes, and vulnerability of the unique biomes of South Africa. An earth system model forced by 15 CMIP4 GCM runs projects a global expansion of warm deserts by 10 to 34% by 2100, with much of this due to a southward expansion of the Sahara (Zeng and Yoon, 2009). Niche modeling of tropical rainforests under a 4ºC warming projects expansion in Africa up to 50% of rainforest area for 14 CMIP3 GCM runs and contraction of up to 15% of rainforest area for 3 CMIP3 GCM runs. The Congo rainforest generally shows resilience, due to high temperature tolerances and mitigation of water stress by increases in equatorial precipitation (Zelazowski *et al*., 2011).

[INSERT FIGURE 22-5 HERE
Figure 22-5: (a) Potential changes in vegetation between the periods 1961-1990 and 2071-2100, where any of nine combinations of three GCMs (CSIRO Mk3, HadCM3, MIROC 3.2 medres) and three emissions scenarios (B1, A1B,

A2) project change. This is the worst case in comparison to the case of complete agreement of the nine combinations. (b) Vulnerability of ecosystems to biome shifts based on historical climate (1901-2002) and projected vegetation (2071-2100), where all nine GCM-emissions scenario combinations agree on the projected biome change. Source: Gonzalez *et al.* (2010).]

As a first-order response to continental warming, species may be expected to shift their ranges poleward and up mountain slopes, however it has been difficult to directly attribute this shift to climate change. Hockey and Midgley (2009) and Hockey et al. (2011) do find that some South African bird species have moved farther south over recent decades, but that many of these shifts can be explained by other factors; in particular, there is evidence of a very strong response to recent and ongoing land use change. Foden et al. (2007) find that an aloe of the Namib is experiencing a range contraction that is consistent with increased heat-related mortality at its warming tropical extreme coupled with an inability to expand poleward quickly enough to compensate. Meanwhile, Raxworthy et al. (2008) note a general upslope movement of amphibian species on a Madagascan massif for which local warming appears to be the most parsimonious explanation. Validation of niche model results against field observations shows limitations to model accuracy (Hanspach *et al.*, 2011).

22.3.2.1.1. Forests

The impacts of climate change on forests are not clear since some studies predict an increase in productivity while others indicate the reverse (Chidumayo *et al.*, 2011). Forest cover in Africa currently stands at 675 million hectares, which represented 21% of global carbon forest biomass in 2010 and 17% of the world forest area, with the Congo basin in Central Africa being the world's second largest continuous block of tropical rain forest (AMCEN and UNEP, 2006; FAO, 2011; Chidumayo *et al.*, 2011). Forests play a key role in the livelihoods of local communities depending on them (over 30 million indigenous people such as Pygmies in the Congo Basin Forest, and 70% of the total population in Africa; Chidumayo *et al.,* (2011)), providing food (bush meat, roots, tubers, fish, insects, fruits); wood (mainly for cooking and building; wood removal in Africa as fuelwood represented 33% of the global total of fuelwood removal); medicinal products (Colfer *et al.,* 2006; Dudley *et al.,* 2008; Nasi *et al.,* 2008; Manyatsi and Hlophe, 2010; FAO, 2011); other non-timber products; soil conservation; and water quality. They also are important for national economies (forests represent about 6% of gross domestic product (GDP)). For example, in Africa, industrial woods represented about 10% of wood removal that, together with fuelwood, amounted to US$ 2.9 billion in 2005 (FAO, 2011). The loss of forestlands has a dual consequence for climate change by contributing to emission levels and loss of vital carbon sinks and by reducing the adaptive capacity of communities that depend on forest resources.

Forest integrity in Africa is highly threatened by both climate and non-climatic factors. Between 2000 and 2010, the annual deforestation rate was 0.49% despite the fact that there is an increasing trend in Africa of the area planted to forest (2.5% of total forest area), and also for conservation of biodiversity (14%) (FAO, 2011). However, the pressure on these resources is supposed to increase given the needs – among others – for food but also for biofuels. It is also currently recognized that the question of policies (e.g., land tenure) and strategic plans for development will be crucial for the future of forests in Africa (Agrawal *et al.,* 2008; Kalame *et al.,* 2008; Sunderlin *et al.,* 2008; Unruh, 2008; Suivi, 2010; Larson, 2011; Paumgarten and Shackleton, 2011; Somorin *et al.*, 2012). Forests are at the crossroads between development and conservation.

In Africa, the major contribution of greenhouse gases is from deforestation, which contributes 20% to global emissions (Chidumayo *et al.*, 2011). This importance of forests was recognized through the Reducing Emissions from Deforestation and forest Degradation (REDD+) mechanism under the United Nations Framework Convention on Climate Change (UNFCCC). The first experiences indicate the need to synthesize actions toward mitigation and adaptation in the forest sector (Bwango *et al.*, 2000; Guariquata *et al.*, 2007; Nkem *et al.*, 2007; Nyong *et al.*, 2007; Nkem *et al.*, 2008; Biesbroek *et al.*, 2009; Oyden and Innes, 2009; Chia, 2011; Richard *et al.*, 2011). There is also a need to address other causes of forest degradation such as drought (Allen *et al.*, 2010; Martínez-Vilalta *et al.*, 2012).

22.3.2.1.2. Desertification in the Sahel

Analyses of the impacts of climate change and desertification on Sahel vegetation examine two types of trends: (1) short-term changes in grasses and other herbaceous vegetation since 1981; and (2) long-term changes in trees and other woody vegetation since the 1950s.

The remotely sensed normalized difference vegetation index (NDVI), an indicator of herbaceous vegetation, increased at many locations in the Sahel from 1981 to 2007 (Seaquist *et al*., 2006; Heumann *et al*., 2007; Ahmedou *et al*., 2008; Fensholt *et al*., 2009; Bégué *et al*., 2011; de Jong *et al*., 2011). The length of the growing season decreased in that time, suggesting that a more intense but shorter season caused any increase in herbaceous vegetation (de Jong *et al*., 2011). In Mali, increased crop area may have contributed to the increase in NDVI (Bégué *et al*., 2011). Rain-use efficiency (RUE) also seems to show increases at sites in the Sahel from 1981 to 2007 (Prince *et al*., 2007; Fensholt and Rasmussen, 2011). The correlation of RUE with rainfall and higher Sahel rainfall in the 2000s may explain an increasing RUE, so the recent increase may not reflect a reversal of land degradation (Hein and De Ridder, 2006; Fensholt and Rasmussen, 2011; Hein *et al*., 2011). Two characteristics of the NDVI data series constrain interpretation of the NDVI and RUE results. First, NDVI in the Sahel mainly tracks interannual variability of herbaceous vegetation (Anyamba and Tucker, 2005), but not necessarily the long-term condition of perennial vegetation (Gonzalez *et al*., 2012). Second, NDVI coverage began in 1981 at the time of a severe Sahel drought. Interdecadal variability of rainfall led to increases in the 1980s and 1990s, causing the NDVI time series to reflect a short-term rebound from the drought, but not necessarily a long-term recovery (de Jong *et al*., 2011; Fensholt and Rasmussen, 2011).

Tree density and tree species richness indicate vegetation condition over longer time periods than NDVI because trees often withstand years of stress before dying (Allen *et al*., 2010). Field counts of trees, historic aerial photos, and recent satellite images show that tree density has declined since the 1950s at sites in Mali (Ruelland *et al*., 2011) and Senegal (Vincke *et al*., 2010; Gonzalez *et al*., 2012). Field surveys also show that arid species have expanded since the 1950s in Burkina Faso (Wezel and Lykke, 2006; Maranz, 2009; Gonzalez *et al*., 2012), Chad (Gonzalez *et al*., 2012), Mauritania (Gonzalez *et al*., 2012), Niger (Wezel and Lykke, 2006; Gonzalez *et al*., 2012), and Senegal (Gonzalez, 2001; Wezel and Lykke, 2006; Vincke *et al*., 2010). These changes have shifted the Sahel, Sudan, and Guinea zones southward toward moister areas (Gonzalez *et al*., 2012). At one site in Mali, however, tree density did not decrease between 1984 and 2006 (Hiernaux *et al*., 2009). Analyses of temperature, precipitation, population density, and soil indicate that climate dominates in explaining the declines in Sahel tree density and species richness (Gonzalez *et al*., 2012). Because the decline in tree cover may contribute to erosion, reduced soil fertility, and other forms of land degradation, it indicates how climate change may exacerbate desertification.

22.3.2.2. Freshwater Ecosystems

Since the 2008 IUCN red list analysis, it is recognized that freshwater ecosystems, particularly in Africa, will be seriously at risk from climate change (Vié *et al*., 2009; Darwall *et al*., 2011), mainly be through changes in water quantity and quality.

The East African River Valley (EARV) is already experiencing high variability in rainfall and river flows and changes in the geographical distribution of water resources, with the arid to semi-arid areas becoming drier and other areas becoming wetter (Kundzewicz *et al*., 2007). Saline Lake Beseka in the arid Ethiopian rift valley, for instance, has quadrupled from 11.1 km^2 in 1973 to 39.5 km^2 in 2002 due to increased discharge from hot springs (Goerner *et al*., 2009). Much of what is happening to freshwater resources across this region is attributable to increased years of drought, particularly in the past two decades (Boko *et al*., 2007; Solomon *et al*., 2007a), which in turn are reducing river inflows (from reduced runoff), and rising temperatures that are causing increased evaporative water loss. However, other factors such as deforestation, soil erosion, and domestic and industrial pollution, among others, are also observed as important drivers in the reduction of water quality and quantity around the region (Hecky *et al*., 2010; Ndebele-Murisa *et al*., 2010; Beck and Bernauer, 2011; Haande *et al*., 2011). Nevertheless, the amount of water inflow for rivers like the Congo, Nile, and Zambezi are determined mainly by the amount of rainfall within their catchments, a process that is influenced by temperature.

In addition to changes in river inflows, declining water levels have been observed in the freshwaters of this region. Water levels are influenced by evaporation rates with low levels corresponding to drought periods (Ndebele-Murisa *et al*., 2011a; Ndebele-Murisa *et al*., 2011b). Reductions in water levels have also reduced habitats of aquatic organisms, particularly shoaling fish, and adversely affect hydroelectricity production for such reservoirs as Kafue (Zambia), Kariba (Zambia/Zimbabwe), Caborra Bassa (Mozambique), and for stations along the Nile and Shire Rivers in Uganda and Malawi respectively (Mukheibir, 2007). Small variations in climate cause wide fluctuations in the thermal dynamics of freshwaters (Odada *et al*., 2006; Stenuite *et al*., 2007; Verburg and Hecky, 2009; Moss, 2010; Olaka *et al*., 2010). Thermal stratification in the regions' lakes, for instance, isolates nutrients from the euphotic zone, and is strongly linked to hydrodynamic and climatic conditions (Sarmento *et al*., 2006; Ndebele-Murisa *et al*., 2010). Elevated water temperatures as a consequence of elevated air temperatures attributed to global warming have been reported in surface waters of lakes Kivu, Victoria, and Malawi (Odada *et al*., 2006; Verburg and Hecky, 2009; Marshall *et al*., 2009; Hecky *et al*., 2010; Magadza, 2010; Tierney *et al*., 2010; Olaka *et al*., 2010; Magadza, 2011; Woltering *et al*., 2011; Osborne, 2012; Ndebele-Murisa *et al*., 2012) (Table 22-1). Moderate warming is reducing lake water inflows and therefore nutrients, destabilizing plankton dynamics and thereby adversely affecting food resources for higher trophic levels of mainly planktivorous fish (Magadza, 2008; Verburg and Hecky, 2009; Magadza, 2010; Ndebele-Murisa *et al*., 2011a).

[INSERT TABLE 22-1 HERE
Table 22-1: Changes and impacts observed in freshwater lakes of Africa.]

In addition to strengthening the thermocline and density stratification, climate warming is leading to declining depths of light transparent epilimnions in a number of the regions' freshwaters, due to upward shifts in thermoclines in response to elevated temperatures. These changes have been observed in lakes Kivu, Kariba, Malawi, Tanganyika, and Victoria, particularly in the past 50 years (Awange *et al*., 2008; McGinley, 2008; Tumbare, 2008; Njaya *et al*., 2011; Ndebele-Murisa, 2011). This has potential cascading effects on aquatic ecosystems by reducing available nutrients in the upper waters, thereby limiting biological production (Bootsma, 2006; Magadza, 2006; Ogutu-Ohwayo and Balirwa, 2006; Magadza, 2008; Verburg and Hecky, 2009; Hecky *et al*., 2010; Ndebele-Murisa *et al*., 2010; Tierney *et al*., 2010; Urama and Ozor, 2010).

22.3.2.3. Coastal and Ocean Systems

Coastal and ocean systems are crucial for the economies and livelihoods of African countries and climate change will increase their existing challenges (overexploitation of resources, habitat degradation, loss of biodiversity, salinization, pollution, and coastal erosion) (Arthurton *et al*., 2006; UNEP and IOC-UNESCO, 2009; Diop *et al*., 2011). Concern is increasing that coastal areas could suffer directly from climate change, not only through sea level rise, but also from a combination of high sea levels and storm swells (extreme events). For example, a conjunction between storm swell up to 14 m, due to winds generated by a cyclone, and high astronomic tide at 2.2 m was experienced along the Durban coast in March 2007, which led to damages estimated at US$ 100 million (Theron and Rossouw, 2008; Mather and Stretch, 2012). Other climate change impacts (such as flooding of river deltas or an increased migration toward coastal towns due to increased drought induced by climate change (Rain *et al*., 2011) will also affect coastal zones.

22.3.2.3.1. Impacts and vulnerability of coastal ecosystems

Different studies assess the vulnerability of the African coast to sea level rise. They all consider that the impacts could be important, especially in coastal towns.

In Kenya, the impacts of climate change on the entire coastal zone were determined (SEI (2009); see Figure 22-6 (Kebede *et al*., 2012). By 2030, the population at risk of inundation in Mombasa, depending on the scenario used, is estimated to be between 226,780 to 299,550 inhabitants, while economic assets at risk are between US$ 0.9 and 1.19 billion.

[INSERT FIGURE 22-6 HERE
Figure 22-6: Population and economic losses in case of climate change for the whole Kenya coastal zone. Source: (SEI, 2009).]

A similar assessment for Dar es Salaam (Kebede and Nicholls, 2011a) estimated that by 2030, the population and economic assets at risk of extreme water levels of 3.07 to 3.23 m are 30,800 to 140,000 inhabitants and US$ 35.6 to 404.1 million US$. The Dynamic Interactive Vulnerability Assessment (DIVA) model was used to assess the monetary and non-monetary impacts of sea level rise on the entire coast (3,461 km) of Tanzania. It estimated that by 2030, 1,924 to 7,624 km^2 would be lost, mainly through inundation; around 234,000 people per year could be potentially affected by inundation, and between 67,000 and 852,000 people living in inundated areas would be forced to migrate. Without adaptation, residual damages have been estimated at between US$ 20 and 42 million per year, of which around US$ 2.7 million could be due to the loss of wetlands (24% of which will be mangroves). Table 22-2 shows the economic impacts of land inundated in Cape Town based on different sea level rise scenarios.

[INSERT TABLE 22-2 HERE
Table 22-2: Land inundated and economic impacts in Cape Town based on a risk assessment (Cartwrigth, 2008a).]

In Durban as well as in the town of Umhlathuze (Zitholele Consulting, 2009), the assessments were mainly qualitative but it was found that the proposed development plans for tourism in Durban could be affected by sea level rise (Naidu *et al.*, 2006). In South Africa, all the authors recognize the fact that a development too close to the shoreline increases its vulnerability. In the southern Africa region, Namibia has coasts vulnerable to sea level rise located around Walvis Bay (with risks of breaching with potential consequences for the harbor and low-lying places in the town). Diamond mining could also be affected. And in Mozambique the risks are almost everywhere, with potential impacts on the two main harbors (Maputo and Beira), but also problems with tourism infrastructure. This could also induce an increase in environmental refugees in South Africa. The risks of salinization, especially for agriculture and on coral reefs are also considered. (Theron and Rossouw, 2008; Cartwright, 2008b):

Assessments for western (Appeaning Addo *et al.*, 2008; Niang *et al.*, 2010) and northern Africa (Snoussi *et al.*, 2009; World Bank, 2011) arrived at the same conclusions as those for eastern and southern Africa.

22.3.2.3.2. Impacts and vulnerability of marine systems

In Africa, fisheries depend on either coral reefs or coastal upwelling. These two ecosystems will be affected by climate change through ocean acidification, a rise in sea surface temperatures, and changes in upwelling. Ocean acidification (OA) is the term used to describe the process whereby increased CO_2 in the atmosphere, upon absorption, causes lowering of the pH of seawater (CC-OA). Projections indicate that severe impairment of reef accretion by organisms such as corals (Hoegh-Guldberg *et al.*, 2007) and coralline algae (Kuffner *et al.*, 2008) will rank amongst the most important consequences of anthropogenic production of CO_2. The combined effects of global warming and OA have been further demonstrated to lower both coral reef productivity (Anthony *et al.*, 2008) and resilience (Anthony *et al.*, 2011). These effects will have serious consequences for reef biodiversity, ecology, and ecosystem services.

OA is nevertheless a serious issue and together with coral bleaching resulting from climate change, will have lasting effects on tropical reefs and other calcifiers. Of the world's coral reefs, 75% occur in developing countries where they support artisanal fisheries in some of the most populous areas (Pauly *et al.*, 2002). While these fisheries only contribute 2 to 5% to global fishery landings, they are an important protein source for coastal communities in developing countries (Pauly *et al.*, 2002). As these fisheries are already deemed unsustainable (McManus, 1997; Pauly *et al.*, 2002; Newton *et al.*, 2007), a further deterioration of coral reefs will have dire consequences for the food security of humans in these areas. In the WIO, the social adaptive capacity to cope with such change varies (Mcclanahan *et al.*, 2009). The fisheries themselves are also likely to be directly affected by OA, as it has been shown to be deleterious to fish larval development, growth, recruitment, and survival (Ferrari *et al.*, 2011; Franke and Clemmesen, 2011; Baumann *et al.*, 2012; Frommel *et al.*, 2012).

22.3.3. Water Resources

Knowledge has advanced since the AR4 regarding current drivers of water resource abundance in Africa, and in understanding of potential future impacts on water resources from climate change and other drivers. Recent long-term studies assessing changes in surface water resources in Africa provide evidence that climate change is currently having a minimal effect on water abundance (*low confidence*). Findings on the availability of freshwater in the region should be taken with caution considering the systemic limitations associated with inadequate observational data in Africa (Neumann *et al*., 2007; Batisani, 2011). As explained in Chapter 3, surface and groundwater hydrology are governed by multiple, interacting drivers and factors, such as land use change, water withdrawals, and natural climate variability, which make detection and attribution exceedingly difficult.

A growing body of literature amassed since the AR4 suggests that climate change in Africa will have an overall modest effect on future water scarcity relative to other drivers, such as population growth, urbanization, agricultural growth, and land use change (Alcamo *et al*., 2007; Carter and Parker, 2009; MacDonald *et al*., 2009; Taylor *et al*., 2009; Calow and MacDonald, 2009; Abouabdillah *et al*., 2010; Beck and Bernauer, 2011; Droogers *et al*., 2012; Notter *et al*., 2012; Tshimanga and Hughes, 2012) (*medium confidence*). However, broad-scale assumptions about drivers of future water shortages can mask significant sub-regional variability of impacts, particularly in water-stressed regions that are projected to become drier, such as southern and northern Africa. For example, rainfed agriculture in northern Africa is highly dependent on winter precipitation and would be negatively impacted if total precipitation and the frequency of wet days declines across North Africa as has been indicated in recent studies (Born *et al*., 2008; Driouech *et al*., 2010; Abouabdillah *et al*., 2010; García-Ruiz *et al*., 2011). Similarly, climate model predictions based on average rainfall years do not adequately capture interannual and interdecadal variability that can positively or negatively influence surface water runoff (Beck and Bernauer, 2011; Notter *et al*., 2012; Wolski *et al*., 2012). Key challenges for estimating future water abundance in Africa lie in a better understanding of the relationships between evapotranspiration, soil moisture, and land use change dynamics in the context of climate change (Goulden *et al*., 2009a) and to understand how compound risks such as heat waves and seasonal rainfall variability might interact under climate change to impact water resources.

Several studies from Africa point to a future decrease in water abundance, particularly in southern and northern Africa (*high confidence*). For example, all countries within the Zambezi River Basin could contend with increasing water shortages (A2 scenario) although non-climate drivers (e.g., population and economic growth, expansion of irrigated agriculture, and water transfers) are expected to have a greater influence on future water availability than climate change (Beck and Bernauer, 2011). In Zimbabwe, climate change could increase water shortages for downstream users dependent on the Rozva dam (Ncube *et al*., 2011). The Okavango Delta could experience increased drying from both climate change and water withdrawals for irrigation (Murray-Hudson *et al*., 2006; Milzow *et al*., 2010; Wolski *et al*., 2012), and the Breede River in South Africa could face decreased runoff (Steynor *et al*., 2009). For North Africa, Droogers et al. (2012) estimated that climate change will account for 22% of future water shortages in the region while 78% of increased future water shortages can be attributed to socioeconomic factors. Abouabdillah et al. (2010) estimated that higher temperatures and declining rainfall (A2 and B1 scenarios) would reduce water resources in Tunisia, though future land use and socioeconomic changes were not considered in the analysis. Reduced snowpack in the Atlas Mountains could reduce supplies of seasonal meltwater for Morocco (García-Ruiz *et al*., 2011).

Potential climate change impacts on the Nile Basin are of particular concern given the basin's geopolitical and socioeconomic importance. Several studies since the AR4 examine potential changes in water resources for the Nile Basin. Reduced flows in the Blue Nile of around 22% at the Ethiopia-Sudan border are possible due to a combination of climate change (higher temperatures and declining precipitation) and upstream water development for irrigation and hydropower by 2100 (A1B) (McCartney and Menker Girma, 2012). Elshamy et al. (2008) also estimated increased moisture constraints in the Blue Nile Basin by late century driven by higher evapotranspiration under temperature rises between 2°C and 5°C. Beyene et al. (2010) estimated that streamflow in the Nile River will increase in the medium term (2010–2039) but will decline in the latter half of this century (A2 and B1 scenarios) as a result of both declining rainfall and increased evaporative demand, with subsequent diminution of water allocation

for irrigated agriculture downstream from the High Aswan Dam. Kingston et al. (2010) reached a similar conclusion about an initial increase followed by a decline in surface water discharge in the Upper Nile Basin in Uganda but caution that limitations inherent in GCMs hamper the robustness of these findings. Also in eastern Africa, Dessu et al. (2012) reported a potential increase in Mara River flow in the second half of this century (A1B, A2, and B1), though under assumptions of current land use patterns. Seasonal runoff volumes in the Lake Tana Basin, Ethiopia, could decrease by the 2080s under the A2 and B2 scenarios (Abdo *et al*., 2009). In West Africa, the Bani River Basin could experience substantial reductions (60–65%) in runoff (A2 scenario) due to reduced rainfall, with catchment discharge potentially decreasing to levels similar to those observed during the severe drought of the 1980s (Ruelland *et al*., 2012). However, high uncertainty about the direction and magnitude of future precipitation in the Sahel (Chapter 14, WG1) warrants caution. The impact of climate change on total runoff in the Congo Basin could be minimal (A2 scenario) (Tshimanga and Hughes, 2012).

Groundwater resources in Africa could be variably affected by climate change. An analysis by MacDonald et al. (2009) indicated that changes in rainfall would not be expected to directly impact the recharge of deep aquifers in areas receiving below 200 mm rainfall per year, where recharge is negligible due to low rainfall. Groundwater recharge may also not be significantly affected by climate change in areas that receive more than 500 mm per year, where sufficient recharge would remain even if rainfall diminished, assuming current groundwater extraction rates. By contrast, areas receiving between 200 to 500 mm per year, including the Sahel, the Horn of Africa, and southern Africa, may experience a decline in groundwater recharge with climate change if prolonged drought becomes more frequent with climate change.

Coastal aquifers are particularly vulnerable to climate change due to high rates of groundwater extraction, which leads to saltwater intrusion in aquifers, coupled with increased saltwater ingression resulting from sea level rise (Moustadraf *et al*., 2008; Bouchaou *et al*., 2008; Al-Gamal and Dodo, 2009; Kerrou *et al*., 2010). Some studies have shown additional impacts of sea level rise on aquifer salinization with salinity potentially reaching very high levels (Carneiro *et al*., 2010; Niang *et al*., 2010; Research Institute for Groundwater, 2011). Although these effects are expected to be localized, in some cases they will occur in densely populated areas (Niang *et al*., 2010). The profitability of irrigated agriculture in Morocco is expected to decline (under both B1 and A1B scenarios) due to increased pumping of groundwater and increased salinization risk for aquifers (Heidecke and Heckelei, 2010).

The capacity of groundwater delivery systems to meet demand may take on increasing importance with climate change (Calow and MacDonald, 2009). For example, where groundwater pumping and delivery infrastructure is poor, and the number of point sources limited, prolonged pumping can lead to periodic drawdowns and increased failure of water delivery systems or increased saline intrusion (Moustadraf *et al*., 2008). Thus if drought conditions become more prevalent in Africa with climate change, stress on groundwater delivery infrastructures could increase.

Future development of groundwater resources to address direct and indirect impacts of climate change, population growth, industrialization, and expansion of irrigated agriculture, will require much more knowledge of groundwater resources and aquifer recharge potentials than currently exists in Africa. Observational data on groundwater resources in Africa are extremely limited and significant effort needs to be expended to assess groundwater recharge potential across the continent (Taylor *et al*., 2009). A preliminary analysis by MacDonald et al. (2012) indicates that total groundwater storage in Africa is 0.66 million km^3, which is "more than 100 times the annual renewable freshwater resources, and 20 times the freshwater stored in African lakes." However, borehole yields are variable and in many places water yields are relatively low. Detailed analysis of groundwater conditions for water resource planning would need to consider these constraints. In this respect, developing organizational frameworks and strengthening institutional capacities for more effectively assessing and managing groundwater resources in Africa are critically important (Nyenje and Batelaan, 2009; Braune and Xu, 2010).

22.3.4. Agriculture and Food Security

Africa's food production systems are among the world's most vulnerable because of extensive reliance on rainfed crop production, high intra- and inter-seasonal climate variability, recurrent droughts and floods, and persistent poverty that limits the capacity to adapt (Boko *et al*., 2007). In the near term, better managing risks associated with

climate variability may help to build adaptive capacities for climate change (Washington *et al.*, 2006; Cooper *et al.*, 2008; Funk *et al.*, 2008). However, agriculture in Africa could face significant challenges in adapting to climate changes projected to occur by mid-century, as negative effects of high temperatures become increasingly prominent (Battisti and Naylor, 2009; Burke *et al.*, 2009a), thus increasing the likelihood that major crops in Africa could experience significant yield losses (Schlenker and Lobell, 2010). Climate change is likely to reduce the growing season length in Africa (Thornton *et al.*, 2011) although not in all sub-regions (Cook and Vizy, 2012). The composition of farming systems from mixed crop-livestock to more livestock dominated food production could occur as a result of reduced growing season length for annual crops and increases in the frequency and prevalence of failed seasons (Jones and Thornton, 2009; Thornton *et al.*, 2010). Transition zones, where livestock keeping is projected to replace crop cultivation by 2050, occur in the West African Sahel and in coastal and mid-altitude areas in eastern and southeastern Africa (Jones and Thornton, 2009), which currently support 35 million people and are chronically food insecure.

22.3.4.1. Crops

Climate change is very likely to have an overall negative effect on yields of major cereal crops in Africa, with strong regional variability in the degree of yield reduction (Lobell *et al.*, 2008; Liu *et al.*, 2008; Walker and Schulze, 2008; Thornton *et al.*, 2009a; Lobell *et al.*, 2011; Roudier *et al.*, 2011; Berg *et al.*, 2013) (*high confidence*). One exception is in eastern Africa where maize production could benefit from warming at sites above roughly 1,500 m in elevation (A1FI scenario) (Thornton *et al.*, 2009a), although the majority of current maize production occurs at lower elevations thereby implying a change in the distribution of maize cropping. Maize-based systems in southern Africa are among the most vulnerable to climate change, with recent yield losses estimated at 18% (Zinyengere *et al.*, submitted) and 30% (Lobell *et al.*, 2008) relative to current yields. In eastern Africa, simulations that combine all regions south of the Sahara suggest consistently negative effects of climate change on five major staples (rice, wheat, maize, millet, and sorghum) by 2050 (A2 scenario) (Nelson *et al.*, 2009). Wheat production in North Africa is vulnerable to projected warming trends in that region (Eid *et al.*, 2007; Hegazy *et al.*, 2008; Drine, 2011; Mougou *et al.*, 2011).

Climate change will likely have differential impacts on non-cereal crops, with both production losses and gains possible (*low confidence*). Cassava yields in eastern Africa could moderately increase up to 2030s assuming CO2 fertilization and under a range of low to high emissions scenarios (Liu *et al.*, 2008), findings that were similar to Lobell et al. (2008). Suitability for growing cassava could increase with the greatest improvement in suitability in eastern and central Africa (A1B scenario) (Jarvis *et al.*, 2012). However, Schlenker and Lobell (2010) estimated negative impacts from climate change on cassava at mid-century, although these impacts are less than those estimated for cereal crops. Given cassava's hardiness to higher temperatures and sporadic rainfall relative to many cereal crops, it may provide a potential option for crop substitution of cereals as an adaptation response to climate change (Rosenthal and Ort, 2011; Jarvis *et al.*, 2012). Bean yields in Eastern Africa could experience yield reductions by the 2030s under an intermediate emissions scenario (A1B) (Jarvis *et al.*, 2012) and by the 2050s under low (B1) and high (A1FI) emissions scenarios (Thornton *et al.*, 2011). For peanuts, some studies indicate a positive effect from climate change (A2 and B2 scenarios) (Tingem and Rivington, 2009) and others a negative one (Lobell *et al.*, 2008; Schlenker and Lobell, 2010). Bambara groundnuts (*Vigna subterranea*) could benefit from moderate climate change (Tingem and Rivington, 2009) (A2 and B2 scenarios) although the effect could be highly variable across varieties (Berchie *et al.*, 2012). Banana and plantain production could decline in West Africa and lowland areas of East Africa, whereas in highland areas of East Africa it could increase (Ramirez *et al.*, 2011).

Suitable agro-climatic zones for growing economically important perennial crops could significantly diminish, largely due to the effects of rising temperatures (Läderach *et al.*, 2010; Eitzinger *et al.*, 2011a; Läderach *et al.*, 2011a; Eitzinger *et al.*, 2011b; Läderach *et al.*, 2011b; Läderach *et al.*, 2011c). With a 2°C or greater temperature rise by mid-century, suitable agro-climatic zones that are currently classified as very good to good for perennial crops could become more marginal, and what are currently marginally suitable zones could become unsuitable; the constriction of crop suitability could be severe in some cases (Table 22-3). Movement of perennial crops to higher altitudes could mitigate the loss of suitability at lower altitudes but this option is limited. Loss of productivity of high-value crops such as tea, coffee and cocoa would have detrimental impacts on export earnings.

[INSERT TABLE 22-3 HERE
Table 22-3. Projected changes in agro-climatic suitability for perennial crops in Africa under an A2 scenario.]

22.3.4.2. Livestock

Livestock systems in Africa face multiple stressors that could potentially interact with climate change and variability to amplify the vulnerability of livestock-keeping communities. These stressors include rangeland degradation, increased variability in access to water, fragmentation of grazing areas, sedentarization, changes in land tenure from communal towards private ownership, in-migration of non-pastoralists into grazing areas, lack of opportunities to diversify livelihoods, conflict and political crisis, weak social safety nets, and insecure access to land, markets, and other resources (Solomon *et al.*, 2007b; Smucker and Wisner, 2008; Galvin, 2009; Thornton *et al.*, 2009b; Dougill *et al.*, 2010; Ifejika Speranza, 2010).

Loss of livestock under prolonged drought conditions is a critical risk given the extensive rangeland in Africa that is prone to drought. Regions that are projected to become drier with climate change, such as northern and southern Africa, are of particular concern (Solomon *et al.*, 2007b; Masike and Urich, 2008; Thornton *et al.*, 2009b; Dougill *et al.*, 2010; Freier *et al.*, 2012; Schilling *et al.*, 2012). Adequate provision of water for livestock production could become more difficult under climate change. For example, Masike and Urich (2009) estimated that the cost of supplying livestock water from boreholes in Botswana could increase 23% by 2050 due to increased hours of groundwater pumping needed to meet livestock water demands under warmer and drier conditions. Although small in comparison to the water needed for feed production, drinking water provision for livestock is critical, and can have a strong impact on overall resource use efficiency in warm environments (Peden *et al.*, 2009; van Breugel *et al.*, 2010; Descheemaeker *et al.*, 2010; Descheemaeker *et al.*, 2011). Livestock production could be indirectly affected by water scarcity through its impact on crop production and subsequently the availability of crop residues for livestock feeding. Thornton et al. (2010) estimated that maize stover availability per head of cattle could decrease in several East African countries by 2050.

The extent to which increased heat stress associated with climate change could affect livestock productivity has not been well established, particularly in the tropics and sub-tropics (Thornton *et al.*, 2009b), although a few studies point to the possibility that keeping heat-tolerant livestock could become more prevalent in response to warming trends. For example, higher temperatures in lowland areas of Africa could result in reduced stocking of dairy cows in favor of cattle (Kabubo-Mariara, 2008), a shift from cattle to sheep and goats (Kabubo-Mariara, 2008; Seo and Mendelsohn, 2008), and decreasing reliance on poultry (Seo and Mendelsohn, 2008). Livestock keeping in highland areas of East Africa, which is currently cold-limited, would presumably benefit from increased temperatures (Thornton *et al.*, 2010).

22.3.4.3. Agricultural Pests and Diseases

Since the AR4, understanding of how climate change could potentially affect crop and livestock pests and diseases and agricultural weeds in Africa is beginning to emerge. In the case of livestock, Olwoch et al. (2008) estimated that the distribution of the main tick vector species (*Rhipicephalus appendiculatus*) of East Coast fever disease in cattle could be altered by a 2°C temperature increase and changes in mean precipitation resulting in the climatically suitable range of the tick shifting southward. However, a number of environmental and socio-economic factors (e.g., habitat destruction, land use and cover change, and host density) in addition to climatic ones influence tick distribution and need to be considered in assigning causality (Rogers and Randolph, 2006).

Warming in highland regions of eastern Africa could lead to range expansion of crop pests into cold-limited areas (*medium confidence*). For example, in highland arabica coffee-producing areas of eastern Africa, warming trends may result in the coffee berry borer (*Hypothenemus hampei*) becoming a serious threat in coffee-growing regions of Ethiopia, Kenya, Uganda, Rwanda, and Burundi (Jaramillo *et al.*, 2011). Temperature increases in highland banana-producing areas of eastern Africa enhance the risk of altitudinal range expansion of the highly destructive burrowing

nematode, *Radopholus similis* (Nicholls *et al*., 2008); however, no detailed studies have assessed this risk. Ramirez et al. (2011) estimated that increasing minimum temperatures by 2020 could expand the suitable range of Black Leaf Streak disease (Mycosphaerella fijiensis M.) of banana in Angola and Guinea.

Climate change may also affect the distribution of economically important pests in lowland and dryland areas of Africa (*low confidence*). Under A2A and B2A for 2020, Cotter et al. (2012) estimated that changes in temperature, rainfall, and seasonality could result in more suitable habitats for *Striga hermonthica* in central Africa, whereas the Sahel region may become less suitable for this weed. Striga weed infestations are a major cause of cereal yield reduction in Sub-Saharan Africa. Climate change could also lead to an overall decrease in the suitable range of major cassava pests – whitefly, cassava brown streak virus, cassava mosaic geminivirus, and cassava mealybug (Jarvis *et al*., 2012), although southeast Africa and Madagascar could experience increased suitability for cassava pests (Bellotti *et al*., 2012).

22.3.4.4. Fisheries

Fisheries are an important source of food security in Africa. Capture fisheries (marine and inland) and aquaculture combined contribute over one-third of Africa's animal protein intake (Cochrane *et al*., 2009), while in some coastal countries fish contribute up to two-thirds of total animal protein intake (Allison *et al*., 2009). Demand for fish is projected to increase substantially in Africa over the next few decades. To meet fish food demand by 2020, De Silva and Soto (2009) estimated that aquaculture production in Africa would have to increase nearly 500%.

Climate change is beginning to affect African lakes, as evident by increasing surface water temperatures in eastern and southern Africa lakes (O'Reilly *et al*., 2003 as cited in; Brander, 2007; Sitoki *et al*., 2010; Ndebele-Murisa *et al*., 2011b; Marshall, 2012). The effect of warming on fisheries in these lakes is uncertain, with some studies indicating that reduced fisheries output is linked to drought conditions and warming that have reduced upwelling of nutrients necessary for stimulating fish production (O'Reilly *et al*., 2003 as cited in; Brander, 2007; Ndebele-Murisa *et al*., 2011b), and other studies urging caution in over-attributing fisheries decline to climate change given the intense pressures on fisheries from overfishing, pollution, and invasive species (Marshall, 2012). Loss of fisheries and tourism livelihoods resulting from coral bleaching is another critical concern in Africa. An analysis by Cinner et al. (2012) indicated that Tanzania, Kenya, Seychelles, and northwest Madagascar are among the most vulnerable to losses from bleaching because of warm seawater temperatures and high ultraviolet exposure. Livelihood dependency on fishing, and thus high sensitivity to fisheries decline linked to coral bleaching, is particularly great in Tanzania (Burke *et al*., 2011; Cinner *et al*., 2012) and parts of Kenya and Madagascar (Cinner *et al*., 2012).

The vulnerability of national economies to climate change impacts on fisheries can be linked to exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries, and adaptive capacity within the country (Allison *et al*., 2009). An analysis of 132 countries by Allison et al. (2009) estimated that two-thirds of the most vulnerable countries were in Africa. Among these countries, the most vulnerable were Malawi, Guinea, Senegal, and Uganda, due to the importance of fisheries to the poor and the close link between climate variability and fisheries production. Coastal countries of West Africa could experience a significant negative impact from climate change. Lam et al. (2012) projected that by 2050 (under an A1B scenario) the annual landed value of fish for the region could decline by 21%, resulting in a nearly 50% decline in fisheries-related employment and a total annual loss of US$ 311 million to the region's economy.

22.3.4.5. Food Security

Food security in Africa faces multiple stressors stemming from entrenched poverty, environmental degradation, rapid urbanization, high population growth rates, and climate change and variability. The intertwined issues of markets and food security have emerged as an important issue in Africa and elsewhere in the developing world since the AR4. Price spikes for globally traded food commodities in 2007–2008 and food price volatility and higher overall food prices in subsequent years have undercut recent gains in food security across Africa (Brown *et al*., 2009; Hadley *et al*., 2011; Mason *et al*., 2011; Tawodzera, 2011; Alem and Söderbom, 2012; Levine, 2012). Among

the most affected groups are the urban poor, who typically allocate more than half of their income to food purchases (Cohen and Garrett, 2010; Crush and Frayne, 2010), in addition to the rural poor, especially female-headed households (Kumar and Quisumbing, 2011). Although the recent spike in global food prices can be attributed to a convergence of several factors, the expected intensification of climate change could become more important in the future for exerting upward pressure on food prices of basic cereals (Nelson *et al*., 2009; Hertel *et al*., 2010), which could have serious implications for Africa's food security. As the recent wave of food price crises demonstrates, factors in other regions profoundly impact food security in Africa. Much more research is needed to better understand potential interactions between climate change and other key drivers of food prices that act at national, regional, and global scales.

Africa is undergoing both rapid urbanization and subsequent transformation of its food systems to accommodate changes in food processing and marketing as well as in food consumption patterns. Considering the increasing reliance on purchased food in urban areas, approaches for addressing the impacts of climate change on food security will need to encompass a food systems approach (production as well as processing, transport, storage, and preparation) that moves food from production to consumption (Battersby, 2012). Weaknesses in the food system may be exacerbated by climate change in the region as high temperatures increase spoilage and floods damage transportation infrastructure. In this respect, high post-harvest losses in Africa resulting in a large part from inadequate transport and storage infrastructure (Godfray *et al*., 2010; Parfitt *et al*., 2010) are an important concern.

22.3.4.6. Biofuels and Land Use

The potential for first-generation biofuel production in Africa, derived from bioethanol from starch sources and biodiesel production from oilseeds, is significant given the continent's extensive arable lands, labor availability, and favorable climate for biofuel crop production (Amigun *et al*., 2011; Arndt *et al*., 2011; Hanff *et al*., 2011). While biofuel production could have positive energy security and economic growth implications, the prospect of wide-scale biofuel production in Africa carries with it significant concerns about environmental and social sustainability. Among the concerns are competition for land and water between fuel and food crops, adverse impacts of biofuels on biodiversity and the environment, contractual and regulatory obligations that expose farmers to legal risks, changes in land tenure security, and reduced livelihood opportunities for women, pastoralists, and migrant farmers who depend on access to the land resource base (Unruh, 2008; Amigun *et al*., 2011; German *et al*., 2011; Schoneveld *et al*., 2011).

More research is needed to understand fully the socioeconomic and environmental tradeoffs associated with biofuel production in Africa. One critical knowledge gap concerns the effect of biofuel production, particularly large-scale schemes, on land use change and subsequent food and livelihood security. For example, the conversion of marginal lands to biofuel crop production would impact the ability of users of these lands (pastoralists and in some cases women who are allocated marginal land for food and medicinal production) to participate in land use and food production decisions (Amigun *et al*., 2011; Schoneveld *et al*., 2011). In addition, biofuel production could potentially lead to the extension of agriculture into forested areas, either directly through conversion of fallow vegetation or the opening of mature woodland, or indirectly through use of these lands to offset food crop displacement (German *et al*., 2011). Such land use conversion could result in biofuel production reducing terrestrial carbon storage potential (Vang Rasmussen *et al*., 2012a; Vang Rasmussen *et al*., 2012b).

Better agronomic characterization of biofuel crops is another key knowledge gap. For example, little information exists with respect to the agronomic characteristics of the oilseed crop Jatropha (*Jatropha curcas*) under conditions of intensive cultivation across differing growing environments, despite the fact that Jatropha has been widely touted as an appropriate feedstock for biofuel production in Africa because of its ability to grow in a wide range of climates and soils. Oilseed yields of Jatropha can be highly variable, and even basic information about yield potential and water and fertilizer requirements for producing economically significant oilseed yields is scanty (Achten *et al*., 2008; Peters and Thielmann, 2008; Hanff *et al*., 2011). Such knowledge would not only provide a basis for better crop management but would also help to gain better estimates of the extent of water consumption for biofuel production in the context of non-biofuel water-use needs across landscapes. Assessments of Jatropha's potential as

an invasive species and its potential allelopathic effects on native vegetation are also needed, in light of the fact that some countries have designated Jatropha as an invasive species (Achten *et al.*, 2008).

22.3.5. Health

22.3.5.1. Vulnerability

Africa currently experiences high burdens of health outcomes whose incidence and geographic range could be affected by changing temperature and precipitation patterns, including malnutrition, diarrheal diseases, and malaria and other vector-borne diseases, with most of the impact on women and children. Worldwide in 2010, there were 216 million cases of malaria (malaria (81% of episodes were in Africa) and an estimated 655,000 deaths with most (91% deaths) of the cases in Africa; a child dies every minute from malaria (WHO, 2011). In 2011, malaria accounted for 22% of all childhood deaths (WHO, 2011). Globally, nearly one in five deaths in children is due to diarrhea (1.5 million deaths annually) with 80% of deaths in Africa and Asia (UNICEF and WHO, 2009). Other drivers of these health outcomes include inadequate human and financial resources, inadequate public health and health care systems, insufficient access to water and sanitation, and poor governance. For example, of the more than 1 billion Africans, 341 million lack access to safe drinking water and 589 million lack access to improved sanitation, with sub-Saharan Africa having the lowest coverage (UNICEF and WHO, 2008; UNICEF and WHO, 2012). The health impacts of climate change will arise from the interactions of changing weather patterns with generic and place-specific sources of vulnerability (Cardona *et al.*, 2012).

Further emerging vulnerabilities can arise from adaptations implemented in other sectors through, for example, changing habitats for pathogens and their vectors. Building dams for irrigation could lead to epidemics or the spread of leishmaniasis, a debilitating disease endemic in North Africa that can cause facial scarring and stigmatization, affecting primarily women agricultural workers (M.K.Chahed and al, in preparation, Plos journal).

22.3.5.2. Impacts: Current and Future Projections

Literature on the health effects of climate change in Africa generally lags other sectors. Recent climate change appears to be affecting the incidence and geographic range of certain vector-, food-, and water-borne diseases, with projections suggesting increases in their magnitude and extent with additional climate change.

22.3.5.2.1. Food and water-borne diseases

Cholera is primarily associated with poor sanitation, poor governance, and poverty, and could be exacerbated by climate variability and long-term climate change (Rodó *et al.*, 2002; Koelle *et al.*, 2005; Olago *et al.*, 2007; Murray *et al.*, 2012). The frequency and duration of cholera outbreaks are associated with rainfall variability in Ghana and other African countries (de Magny *et al.*, 2007). The El Niño-Southern Oscillation (ENSO) is a driver of cholera pathogenicity and transmission (de Magny *et al.*, 2007). The worst outbreak of cholera in recent African history occurred in Zimbabwe from August 2008 to June 2009. The epidemic was associated with the rainy season and caused more than 92,000 cases and 4,000 deaths. Contamination of water sources spread the disease (Mason, 2009). Poor governance, poor infrastructure, limited human resources, and underlying population susceptibility (high burden of malnutrition) contributed to the severity and extent of the outbreak (Murray *et al.*, 2012).

Climate change is projected to increase child malnutrition (as measured by severe stunting) in sub-Saharan Africa, even taking economic growth into account; the projected increase in central sub-Saharan Africa is 23% by 2050 (Lloyd *et al.*, 2011). Local economic activity and food accessibility can reduce the incidence of malnutrition (Funk *et al.*, 2008; Rowhani *et al.*, 2011). Prevention of future malnutrition would require, in addition, improved socioeconomic conditions and reductions in greenhouse gas emissions (Lloyd *et al.*, 2011). By 2050, the number of malnourished children in sub-Saharan Africa could increase by 24 million due to climate change (Parry *et al.*, 2009b; ADB and IFPRI, 2009).

22.3.5.2.2. Vector-borne diseases

A wide range of vector-borne diseases contribute to premature morbidity and mortality in Africa. New research has been published since the AR4 on malaria, leishmaniasis, Rift Valley fever, and tick- and rodent-borne diseases.

Malaria: Weather and climate are among the determinants of the geographic range and incidence of malaria. The association between temperature and malaria varies regionally, with some studies concluding it is nonlinear and others quadratic or exponential (Chaves and Koenraadt, 2010; Paaijmans *et al*., 2010a; Alonso *et al*., 2011; Gilioli and Mariani, 2011). Total precipitation, rainfall patterns, and the water temperature of breeding sites will likely alter disease susceptibility (Bomblies and Eltahir, 2010; Paaijmans *et al*., 2010b; Afrane *et al*., 2012). ENSO events also may contribute to malaria epidemics (Mabaso *et al*., 2007; Ototo *et al*., 2011). The complexity of the malaria transmission cycle makes it difficult to determine whether the distribution of the pathogen and vector are already changing due to climate change.

Research continues to support the AR4 finding that climate change could affect the geographic range and incidence of malaria, particularly along the current edges of its distribution, with contractions and expansions, and increasing and decreasing incidence (Yé *et al*., 2007; Peterson, 2009a; Parham and Michael, 2010; Paaijmans *et al*., 2010b; Alonso *et al*., 2011; Chaves *et al*., 2011; Egbendewe-Mondzozo *et al*., 2011; Paaijmans *et al*., 2012; Parham *et al*., 2012; Ermert *et al*., 2012), depending on other drivers, such as public health interventions, factors influencing the geographic range and reproductive potential of malaria vectors, land use change (e.g., deforestation), and drug resistance, as well as the interactions of these drivers with weather and climate patterns (Chaves *et al*., 2008; Kelly-Hope *et al*., 2009; Paaijmans *et al*., 2009; Saugeon *et al*., 2009; Artzy-Randrup *et al*., 2010; Dondorp *et al*., 2010; Gething *et al*., 2010; Jackson *et al*., 2010; Kulkarni *et al*., 2010; Loha and Lindtjørn, 2010; Tonnang *et al*., 2010; Stern *et al*., 2011; Caminade *et al*., 2011; Omumbo *et al*., 2011; Afrane *et al*., 2012; Edlund *et al*., 2012; Gething *et al*., 2012; Githeko *et al*., 2012; Himeidan and Kweka, 2012; Jima *et al*., 2012; Lyons *et al*., 2012; Ermert *et al*., 2012; Mordecai *et al*., 2013). Because various *Anopheles* species are adapted to different climatic conditions, changing weather and climate patterns could affect species composition differentially (Afrane *et al*., 2012).

Consensus is growing that highland areas, especially in East Africa, will experience increased malaria epidemics, with areas above 2,000 m particularly affected (Pascual *et al*., 2006; Peterson, 2009b; Lou and Zhao, 2010; Paaijmans *et al*., 2010a; Ermert *et al*., 2012; Gething *et al*., 2012). Reasons for different projections across models include using GCMs versus regional climate models (Ermert *et al*., 2012); the need for finer-scale and higher-resolution models of the sharp climate variations with altitude (Bouma *et al*., 2011); and the extent to which other drivers of the geographic range and incidence of malaria are included, including how these drivers interact with climate change.

Directly or indirectly, climate change may increase the incidence and geographic range of leishmaniasis. Leishmaniasis, a highly neglected disease, has recently become a significant health problem in northern Africa (Postigo, 2010) with a rising concern in western Africa because of co-infection with HIV (Kimutai *et al*., 2006). The epidemiology of the disease appears to be changing (Dondji, 2001; Yiougo *et al*., 2007; WHO, 2009; Postigo, 2010). Previously an urban disease, leishmaniasis now has a peri-urban distribution linked to changes in the distribution of the rodent host and of the vector over the last 20 years in Algeria (Aoun *et al*., 2008). Cutaneous leishmaniasis has expanded its range from its historical focus at Biskra into the semi-arid steppe, with an associated upward trend in reported cases. In Morocco, epidemic transmission of leishmania major (vector *Phlebotomus papatasi*) occurred in 2009 with occasional outbreaks of up to 2,000 cases, followed by long periods with few or no cases (Rhajaoui, 2011). The disease has spread to areas in West Africa and East Africa (Dondji, 2001; Yiougo *et al*., 2007; WHO, 2009). Outbreaks of zoonotic cutaneous leishmaniasis (ZCL) have become more frequent in Tunisia, Algeria, and Morocco, where the disease is endemic. In Tunisia, weather patterns, including heavy rainfall up to two years prior and warmer than average temperature three to six months prior to an outbreak, are associated with changes in the geographic range and incidence of the disease and/or changes in rodent density and density of sandfly species (Salah *et al*., 2007; Interim Technical Report, 2011). Environmental modifications, such as dam construction, can change

the temperature and humidity of the soil and thus affect vegetation that may result in changes in the composition and density of sandfly species and rodent vectors.

Rift Valley fever (RVF) epidemics in the Horn of Africa are associated with altered rainfall patterns. Additional climate variability and change could further increase its incidence and spread. Rift Valley fever is endemic in numerous African countries, with sporadic repeated epidemics. Epidemics in 2006–2007 in the Horn of Africa (Nguku *et al*., 2007; WHO, 2007; Adam *et al*., 2010; Andriamandimby *et al*., 2010) and southern Africa were associated with heavy rainfall (Chevalier *et al*., 2011), strengthening earlier analyses by Anyamba et al. (2009) showing that RVF epizootics and epidemics are closely linked to the occurrence of the warm phase of ENSO and La Nina events (Linthicum *et al*., 1999; Anyamba *et al*., 2012) and elevated Indian Ocean temperatures. These conditions lead to heavy rainfall and flooding of habitats suitable for the production of the immature *Aedes* and *Culex* mosquitoes that serve as the primary RVF virus vectors in East Africa. Flooding of mosquito habitats also may introduce the virus into domestic animal populations.

Changing weather patterns could expand the distribution of ticks causing animal disease, particularly in East and South Africa. About 300 million Africans depend on livestock for their livelihood. In sub-Saharan Africa, livestock diseases cost an estimated US$ 2 billion, aggravating poverty, hunger, and disease in humans. Globally, six million cattle are exposed to ticks annually, with more than one-third of these in Africa. Theileriosis (East Coast Fever) ticks are vectors and agents of diseases, causing anemia and skin damage that expose cattle to secondary infections. Habitat destruction, land use and cover change, and host density also affect tick distribution (Rogers and Randolph, 2006). Using a climate envelope and a species prediction model, Olwoch et al. (2007) found that East Africa and South Africa are the most vulnerable to climate-induced changes in tick distributions and tick-borne diseases: more than 50% of the 30 *Rhipicephalus* species examined showed significant range expansion and shifts. More than 70% of this range expansion was found in economically important tick species.

Approximately 243 million people are infected with schistosomiasis, of which 90% live in underdeveloped areas of Africa (WHO, 2013). Water resource development, such as irrigation dams recommended for adaptation in agriculture, can amplify the risk of schistosomiasis (Huang and Manderson, 1992; Hunter *et al*., 1993; Jobin, 1999). Migration and sanitation play a significant role in the spread of schistosomiasis from rural areas to urban environments (Babiker *et al*., 1985; WHO, 2013). Temperature and precipitation patterns may play a role in transmission (Odongo-Aginya *et al*., 2008; Mutuku *et al*., 2011; Huang *et al*., 2011). A relation between climate variability and schistosomiasis has been noted elsewhere (Huang *et al*., 2011) and there is the need for further research in Africa to assess the possible climate change impacts on the disease.

Researchers have found a strong relationship between the seasonal pattern of meningococcal meningitis and climate (environmental factors) this includes a relationship between the seasonal pattern of the harmattan dusty winds and the onset of the epidemic and the seasonal cycle of meningitis. Links with other environmental factors affected by climate change like wind and humidity have been noted. Epidemics occur throughout Africa in the dry season and coincide with periods of very low humidity and dusty conditions. The epidemics disappear with the onset of the rains (Molesworth *et al*., 2003). Recently, other researchers have corroborated with earlier hypothized relationships between weather and meningitis, (Yaka *et al*., 2008; Palmgren, 2009; Roberts, 2010; Dukić *et al*., 2012). Further, in the northern region of Ghana, a follow-on study to Hodgson et al. 2001 by Hayden et al. (revision submitted) found that exposure to smoke from cooking fires increased the risk of contracting meningococcal meningitis. This increased risk suggests that exposure to elevated concentrations of air pollutants, such as carbon monoxide (CO) and particulate matter, may be linked to illness. More research is needed to clarify the impact of climate change on air quality and linkages with meningitis. Researchers have quantified the relationship between the environment and the location of the epidemics suggesting that there are connections between epidemics and regional climate variability (Molesworth *et al*., 2003; Sultan *et al*., 2005; Thomson *et al*., 2006). This will be beneficial in predicting location and onset of epidemics in Early Warning Systems.

Novel hantaviruses with unknown pathogenic potential have been identified in some insectivores (shrews and a mole) in Africa (Klempa, 2009). Climate change could alter the natural reservoirs of hantaviruses. Changes in the geographical distribution of the rodent carriers could deliver hantaviruses to new regions, altering species composition in ways that could be epidemiologically important (Klempa, 2009). Exacerbated food insecurity due to

climate change could further compromise the poor nutrition of people living with HIV/AIDs (Drimie and Gillespie, 2010). Laboratory studies suggest that the geographic range of the tsetse fly (Glossina species), the vector of human and animal trypanosomiasis in Africa, may be reduced under future scenarios (Terblanche *et al*., 2008).

Heat waves and heat-related health effects are only beginning to attract attention in Africa. Recent studies in West and southern Africa indicate heat-related health effects may be of concern (Dapi *et al*., 2010; Mathee *et al*., 2010).

Climate change is anticipated to affect the sources of air pollutants as well as the ability of pollutants to be dispersed in the atmosphere (Denman *et al*., 2007). Assessments of the impacts of projected climate change on air quality indicate that changes in surface temperature, land cover, and lightning may alter natural sources of ozone precursor gases and consequently ozone levels over Africa (Stevenson *et al*., 2005; Brasseur *et al*., 2006; Zeng *et al*., 2008). However, insufficient climate and emissions data for Africa prevent a more comprehensive understanding of the nature of the changes to air pollution.

22.3.6. Human Security

Human security of people in Africa is particularly threatened by the impacts of climate variability. Adverse climate events impact all aspects of human security, either directly or indirectly (For more details see Chapter 12). Water stress, land use and food security, health security, violent conflicts, changing migration patterns, and human settlements are interrelating issues between climate change and human with particular relevance on the African continent.

22.3.6.1. Economic Security

The ultimate damages of climate change may significantly affect economic growth and the ability to trade (Lecocq and Shalizi, 2007; Ruppel and Ruppel-Schlichting, 2012). The impacts on the agricultural sector in Africa are probably of the most direct and profound nature. In Tanzania, climate volatility could have severe implications for poverty as agriculture accounts for about half of gross production, and employs about 80% of the labor force (Ahmed *et al*., 2011). For Namibia, general equilibrium model simulations indicate that over 20 years, annual losses to the Namibian economy could be up to 5% of GDP, due to the impact that climate change will have on its natural resources alone (Reid *et al*., 2008). Such losses are detrimental, considering that unemployment, poverty, the HIV/AIDS pandemic, and household food insecurity are among the main problems facing the country (Ruppel, 2011). Ghana's agricultural and economic sector with cocoa being the single most important export product is particularly vulnerable, since cocoa is particularly prone to the effects of a changing climate, which has been central to the country's debates on development and poverty alleviation strategies (WTO Trade Policy Review, 2008; Black *et al*., 2011c). A decline in lake levels in Ghana caused by reduced rainfall over the last 40 years, is another critical aspect with regard to economic development because the demand for power is increasing due to economic growth and hydroelectric power stations generate 80% of Ghana's total national power production (Kuuzegh, 2007; Black *et al*., 2011c).

22.3.6.2. Violent Conflicts

While there seems to be consensus that the environment is only one of several interconnected causes of conflict and is rarely considered to be the most decisive factor (Kolmannskog, 2010), it remains disputed whether the changing climate increases the risk of civil war in Africa. In sub-Saharan Africa, climate variability is a poor predictor of armed conflict. Instead, African civil wars can be explained by generic structural and contextual conditions: prevalent ethno-political exclusion, poor national economies, and the collapse of the Cold War system (Buhaug, 2010). Other research also focusing on sub-Saharan Africa comes to the diametrically opposite result, concluding that warming does increase the risk of civil war in Africa (Burke *et al*., 2009b). Strong historical linkages exist between civil war and temperature in Africa, with warmer years leading to significant increases in the likelihood of war. A roughly 54% increase in armed conflict incidence is predicted by 2030, or an additional 393,000 battle deaths

if future wars are as deadly as recent wars. It has been argued that conflicts are more likely in regions with higher ecosystem productivity (possibly resulting from vegetation recovery after populations are displaced out of conflict zones), and that increased levels of malnutrition are related to armed conflicts (Rowhani *et al.*, 2011). However, with an emphasis on the role of renewable resources such as freshwater and arable land, it is argued that as a long-term trend, population growth and resource scarcities result in violent competition (Raleigh, 2010) while short-term causes may trigger the outbreak of conflict (Hendrix and Glaser, 2007). Distributional conflicts will arise due to the degradation of natural resources as a result of overexploitation and global warming (Kumssa and Jones, 2010). Such distributional conflicts are, for example, occurring in Somalia, and armed conflict may exacerbate the drought. An important part of the war economy in Somalia, namely the commercial production and export of charcoal resulting in deforestation, is one example of environmental degradation contributing to drought (Kolmannskog, 2010).

22.3.6.3 Migration

Human migration in Africa has social, political, demographic, economic, and environmental drivers, which may operate independently or in combination(Perch-Nielsen *et al.*, 2008; Piguet, 2010; Foresight, 2011; Piguet *et al.*, 2011; Black *et al.*, 2011a; Ruppel, 2012). People migrate either temporarily or permanently, within their country or across borders (Warner *et al.*, 2010; Kälin and Schrepfer, 2012). The evidence base in the field of migration in Africa is both varied and patchy. Different assessments of future trends have recently produced contradictory conclusions (e.g., ADB, (2011); Tacoli, (2011)). A global study conducted in 2009 reveals that in 2008, at least 36 million people were newly displaced by sudden-onset natural disasters such as floods and storms, including 697,066 people in Africa. The number of displaced people in Africa has increased from 697,066 in 2008 to 1.1 million in 2009 and 1.7 million in 2010 (IDMC, 2011). It is likely that many more are displaced due to other climate change-related drivers, including slow-onset disasters, such as drought and sea level rise (UN-OCAH and IDMC, 2009). With regard to forced migration in sub-Saharan Africa, it was found that one additional natural disaster per year could lead to an increase in net migration of 0.6 per 1,000 (Naude, 2010). One approach in assessing future migration potentials, with considerable relevance to the African context, focused on capturing the net effect of environmental change on aggregate migration through analysis of both its interactions with other migration drivers and the role of migration within adaptation strategies, rather than identifying specific groups as potential 'environmental migrants' (Foresight, 2011). Even if Africa's population doubles by 2050 to 2 billion (Lutz and Kc, 2010) and the potential for displacement rises as a consequence of the impact of rapid-onset climate events, recent analyses (Foresight, 2011; Black *et al.*, 2011b) show that the picture for future migration is much more complex than previous assessments of a rise in climate refugees suggest, and relates to the intersection of multiple drivers with rates of global growth, levels of governance, and climate change.

Besides low-lying islands and coastal and deltaic regions, sub-Saharan Africa is one of the regions that would particularly be affected by environmentally induced migration (Gemenne, 2011a). Case studies from Somalia and Burundi emphasize the interaction of climate change, disaster, conflict, displacement, and migration (Kolmannskog, 2010). In Ghana for example, an African country with few conflicts caused by political, ethnic, or religious tensions, and thus with migration drivers more likely related to economic and environmental motivators (Tschakert and Tutu, 2010), some different types of migration flows are considered to have different sensitivity to climate change (Black *et al.*, 2011a). The floods of the Zambezi River in Mozambique in 2008 have displaced 90,000 people, and it has been observed that along the Zambezi River Valley, with approximately 1 million people living in the flood-affected areas, temporary mass displacement is taking on permanent characteristics (Jäger *et al.*, 2009; Warner *et al.*, 2010).

The empirical base for major migration consequences is very weak (Lilleør and Van den Broeck, 2011; Black *et al.*, 2011a; Gemenne, 2011b) and non-existent for international migration (Marchiori *et al.*, 2011). Even across the same climate disaster, the response can vary (Findlay, (2011); Gray, (2011) for Kenya and Uganda; Raleigh, (2011) for the African Sahel States). Mobility is indeed a strategy (not a reaction) to high levels of climatic variation that is characteristic of Africa (Tacoli, 2011) and the specifics of the response are determined by the economic context of the specific communities.

22.3.7. Urbanization

Climate change affects the size and characteristics of rural and urban human settlements in Africa. Urbanization through migration is also leading to new vulnerabilities as new migrants face significant ecological issues including floods, etc. (Seto, 2011). The problems associated with voluntary or involuntary environmentally induced migration to Africa's large and intermediate cities will be exacerbated as a result of climate change. Migration flows can be observed away from flood-prone localities, as well as potentially large-scale internal and cross-border mobility away from agricultural zones undermined by changing climatic conditions or declining water availability (UN-Habitat and UNEP, 2010). African inland cities are threatened by the potential risk of water shortages, damage to infrastructure, and desiccating vegetation due to the impacts of climate change.

The urban population in Africa will treble by 2050, increasing by 0.8 billion (UN DESA, 2010). African countries are experiencing some of the world's highest urbanization rates (UN-Habitat, 2008a). Many of Africa's evolving cities are unplanned and have been associated with the uncontrolled growth of informal settlements, inadequate housing and basic services, and increasing urban poverty (Yuen and Kumssa, 2011).[6]

[FOOTNOTE 6: However, community-driven upgrading may contribute to reducing the vulnerability of such informal areas (for more details see Chapter 8).]

Climate change, with its associated erratic rainfall and extreme weather events, is expected to have significant impacts on urbanization in Africa. In particular, the majority of migration flows observed in response to environmental change are internal (Jäger *et al*., 2009; Tacoli, 2009). In particular, extreme climate variations and, more specifically, water shortages, may cause abrupt changes in human settlements and urbanization patterns in sub-Saharan Africa more than anywhere else in the world (Marchiori *et al*., 2012). Rural–urban migration has typically been motivated by livelihood opportunities, and traditionally involves moving into large towns and cities (Barrios *et al*., 2006; Annez *et al*., 2010). Such rapid rates of urbanization represent a burden on the economies of African urban areas, due to the massive investments needed to create job opportunities and provide infrastructure and services. Basic infrastructure services are not keeping up with urban growth, which has resulted in a decline in the coverage of many services, compared to 1990 levels (Banerjee *et al*., 2007).

Thus, African cities and towns represent some of the most vulnerable to the impacts of climate change and climate variability (Boko *et al*., 2007; Diagne, 2007; Dossou and Gléhouenou-Dossou, 2007; Douglas *et al*., 2008; Adelekan, 2010; Kithiia, 2011). The impacts of climate change, which could be seen as one of the key systematic shocks, have the potential to disrupt entire urban systems as well as their sustainability (UN-Habitat, (2010); for further details see Chapter 8).

Furthermore, most of those migrating from rural areas have limited skills and education. This means that they often end up in the informal sector of the urban economy and settle in squatter areas on the peripheries of cities where poverty, overcrowding, unemployment, crime and environmental degradation are common (Yuen and Kumssa, 2011). For instance, despite African cities generating about 55 to 60% of the continent's total GDP, a massive 43% of its urban populations live below the poverty line (Eriksen *et al*., 2010). Moreover, sub-Saharan African countries have the highest levels of urban poverty in the world (Eriksen *et al*., 2010).

Squatter and poor areas typically lack provisions to reduce flood risks or to manage floods when they happen (Douglas *et al*., 2008). Floods are already exerting considerable impacts on cities and smaller urban centers in many African nations – for instance, the heavy rains in East Africa in 2002 that brought floods and mudslides, forcing tens of thousands to leave their homes in Rwanda, Kenya, Burundi, Tanzania, and Uganda and the very serious floods in Port Harcourt and in Addis Ababa in 2006 (Douglas *et al*., 2008).

Another impact of climate change on coastal settlements in Africa is sea level rise along coastal zones, which is likely to disrupt economic activities such as tourism, fisheries, and mining. More than a quarter of Africa's population lives within 100 km of the coast and about 12% of the urban population lives in low-elevation coastal zones. Coastal zones will experience significant impacts arising from storms, floods, and sea level rise. In Africa, coastal cities such as Cape Town, Maputo and Dar es Salaam with large and growing populations will be affected

(Bunce *et al*., 2010). Despite being the most developed of Africa's urban areas, coastal cities are particularly vulnerable to sea level rise. Nearly 60% of Africa's total population living in low-elevation coastal zones is urban, representing 11.5% of the region's total urban population (UN-Habitat, 2008a). Because of their large adaptation deficit, African coastal cities are poorly equipped to deal with sea level rise and will be among the most adversely affected, leading to devastating consequences (UN-Habitat, 2008a). All of these climate change impacts affect the poor and vulnerable most severely (Douglas *et al*., 2008; Kithiia, 2011), making climate change one of the greatest developmental challenges facing the continent's cities.[7]

[FOOTNOTE 7: For more details see Chapter 8.]

African small- and medium-sized cities have "low levels of capacity to adapt to the current range of climate variability, let alone any future climate impacts" (UN-Habitat, 2011). In other words, they have a high adaptation deficit (Satterthwaite et al., (2009); for more details see Chapter 7 and Chapter 8). The shortfall in infrastructure in African cities is a particularly critical concern, as adaptation is often framed in terms of infrastructural changes. It is not possible, however, "to climate-proof infrastructure that is not there" (Satterthwaite *et al*., 2009). It is also important to question the appropriateness of hard infrastructural responses such as seawalls and channelized drainage lines that are costly and often maladaptive (Dossou and Gléhouenou-Dossou, 2007; Douglas *et al*., 2008; Kithiia and Lyth, 2011).

The reason for the high level of vulnerability and low adaptive capacity has less to do with climate change (Kithiia, 2011) and more to do with structural factors, particularly local governments with poor capacities and resources. Weak local government creates and exacerbates a large number of problems, including the lack of appropriate regulatory structures and mandates; poor or no planning; lack of or poor data; lack of disaster risk reduction strategies; poor servicing and infrastructure (particularly waste management and drainage); uncontrolled settlement of high-risk areas such as floodplains, wetlands, and coastlines; ecosystem degradation competing development priorities and timelines; and a lack of coordination among government agencies (AMCEN and UNEP, 2006; Diagne, 2007; Dossou and Gléhouenou-Dossou, 2007; Mukheibir and Ziervogel, 2007; Douglas *et al*., 2008; Roberts, 2008; Adelekan, 2010; Kithiia and Dowling, 2010; Kithiia, 2011).

22.4. Adaptation

22.4.1. Introduction

Since 2007, Africa has gained a wealth of experience in conceptualizing, planning and beginning to implement and support adaptation activities, from local to national levels and across a growing range of sectors (sections 22.4.4 and 22.4.5). However, across the continent, most of the adaptation to climate variability and change is reactive in response to short-term motivations, is occurring autonomously at the individual / household level, and lacks support from government stakeholders and policies (Vermuelen et al., 2008; Ziervogel et al., 2008; Berrang-Ford et al., 2011; Thorn, forthcoming).

22.4.2. Adaptation Needs, Gaps, and Adaptive Capacity

Africa's urgent adaptation needs stem from the continent's foremost vulnerability to climate change and its overall low levels of adaptive capacity (section 22.3). The literature does also highlight a number of inherent adaptation-related strengths in Africa: the continent's wealth in natural resources, well-developed social networks, and longstanding traditional mechanisms of managing variability through, for example, crop and livelihood diversification, migration and small-scale enterprises, all of which are underpinned by local or indigenous knowledge systems for sustainable resource management (Cooper et al., 2008; Nielson, 2010; UNFCCC, 2007; Nyong et al, 2007; Macchi et al., 2008; Castro et al., 2012; Eyong, 2007). However, it is uncertain to what extent these strategies will be capable of dealing with future changes, among them climate change and its interaction with other development processes (van Aalst et al., 2008; Leary et al, 2007; Paavola, 2008; Conway, 2009; Jones, 2011b). Since Africa is extensively exposed to a range of multiple stressors (section 22.3) that interact in complex

ways with longer term climate change, adaptation needs are broad, encompassing institutional, social, physical and infrastructure needs, ecosystem services and environmental needs, and financial and capacity needs. Towards elucidating these needs, least developed countries in Africa have used the National Adaptation Plan of Action (NAPA) process to assess vulnerabilities, explore impacts, and identify adaptation priorities (UNFCCC, 2002), and many African countries have conducted technology needs assessments , including Cote d'Ivoire, Ethiopia, Kenya, Ghana, Mali, Morocco, Mauritius, Rwanda, Senegal, Sudan, and Zambia (GEF Evaluation Office, 2011).

Analyses reveal that making climate change information more reliable and accessible is one of the most pressing and cross-cutting adaptation needs. As noted in the AR4 and emphasised in subsequent literature, monitoring networks in Africa are insufficient and characterised by sparse coverage and short and fragmented records, which makes modelling difficult (Boko et. al., 2007; Goulden et al., 2009b; Ziervogel & Zermoglio, 2009; Jalloh, Sarr et al., 2011). Adding to this is the shortage of relevant information and skills, in particular for downscaling climate models and using scenario outputs for development and adaptation planning, which is exacerbated by under-resourcing of Meteorological Agencies and related organisations; and the capacity of civil society and government organisations' to access, interpret and use climate information for planning and decision making (Ziervogel & Zermoglio, 2009; Brown et al., 2010; Ndegwa et al., 2010; Jalloh, Sarr et al., 2011). Information-related needs include additional vulnerability and impact assessments with greater continuity in countries , country-specific socio-economic scenarios, and greater knowledge on costs and benefits of different adaptation measures (UNFCCC, 2007; AAP, 2012).

Given its dependence on natural-resource based economies, most research on strengthening adaptive capacity in Africa is focused on natural resource-based livelihoods, such as agriculture, forestry or fisheries (Collier et al., 2008; Berrang-Ford et al., 2011). In this regard, many African countries have prioritised the following knowledge needs: comprehensive programmes that promote adaptation through a more holistic development approach, including integrated programmes on desertification, water management and irrigation; promoting sustainable agricultural practices and the use of appropriate technologies and innovations to address shorter growing seasons, extreme temperatures, droughts, and floods; developing alternative sources of energy; and approaches to deal with water shortages, food security and loss of livelihoods (AAP, 2012; Sissoko et al 2011; Jalloh and Roy-Macauley, 2011; Bryan et al., 2009; Chikozho, 2010; Eriksen & Silva, 2009, Gbetibouo et al., 2010). The rural emphasis is now being expanded through a growing focus on requirements for enhancing urban adaptive capacity (Lwasa, 2013). The literature, however, stresses the vast variety of contexts that shape adaptation and adaptive capacity - even when people are faced with the same stimuli, responses vary greatly (Cooper et al., 2008; Vermuelen et al., 2008; Ziervogel et al., 2008; Gbetibou, 2009; Westerhoff & Smit, 2009).

Despite significant data and vulnerability assessment gaps, there is consensus that this should not be used as an excuse to delay action on adaptation (UNFCCC, 2007; Jobbins, 2011). Recent analyses emphasise the significant resources and increased financial, technical and technological support needed to both address Africa's current adaptation deficit and to protect rural and urban livelihoods, societies and economies from climate change impacts at different local scales, with estimates of adaptation costs between US$20-30 billion per annum over the next couple of decades (LDC Expert Group, 2011; Parry et al, 2009a; Fankhauser and Schmidt-Traub, 2010; Watkiss et al, 2010; AfDB, 2011; Dodman and Carmin, 2011; Smith et al, 2011).

22.4.3. Adaptation, Equity, and Sustainable Development

Multiple uncertainties in the African context mean that successful adaptation will depend upon developing resilience in the face of uncertainty (Conway, 2011). The inadequacy of developmental strategies to counter current climate risks reinforces the need for strong inter-linkages between adaptation and development, and for low-regrets adaptation strategies that produce developmental co-benefits (high confidence) (Bauer and Scholz, 2010; Smith et al., 2011). As adaptation and local adaptive capacity are affected by inequalities, an effective adaptation response necessitates differentiated and targeted actions from the local to national levels, given the differentiated social impacts based on gender, age, disability, ethnicity, geographical location, livelihood, and migrant status of climate change (Tanner and Mitchell, 2008; IPCC, 2012). While adaptation efforts in Africa have not sufficiently prioritized equity and social justice, including the differential distribution of adaptation benefits and costs (Burton et al, 2002;

Thomas and Twyman, 2005; Madzwamuse, 2010), some valuable experience has been gained recently on gender equity in adaptation, human rights based-approaches, and involvement of vulnerable or marginalized groups such as indigenous peoples and children, aged and disabled people, internally displaced persons and refugees (Unicef, 2010; Unicef, 2011; Tanner and Seballos, 2012; Romero González et al., 2011; IDS, 2012; African Development Forum, 2010; Levine et al., 2011) (Table 22-4).

[INSERT TABLE 22-4 HERE
Table 22-4: Cross-cutting approaches for equity and social justice in adaptation.]

22.4.4. Experiences in Building the Governance System for Adaptation, and Lessons Learned

22.4.4.1. Introduction

Section 22.4 assesses progress made in developing policy, planning and institutional systems for climate adaptation at regional, national and sub-national levels in Africa. This includes an assessment of community-based adaptation, as an important local level response, and a consideration of adaptation decision making and monitoring.

22.4.4.2. Regional and National Adaptation Planning

While regional policies and strategies for adaptation, as well as transboundary adaptation, are still in their infancy, sub-regional institutions have begun to formulate strategies for climate change. For example, the Southern African Development Community and the Lake Victoria Basin Committee are developing Climate Change Strategies and Action Plans, and efforts are being made by six highly-forested Congo basin countries (Cameroon, Central African Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon, and the Republic of Congo) to coordinate conservation and sustainable forest management of the Central African forest ecosystem, and obtain payments for ecosystem services (Harmeling et al, 2011; African Development Bank, 2012).

At the national level, African countries have initiated comprehensive planning processes for adaptation by developing National Adaptation Programmes of Action (NAPAs) or National Climate Change Response Strategies (NCCRS); implementation is, however, lagging and integration with economic and development planning is limited but growing (high confidence). As of December 2011, 32 Least Developed Countries in Africa had developed NAPAs, with the exception of Equatorial Guinea and Somalia. Prioritized adaptation measures in the NAPAs tend to focus on agriculture, food security, water resources, forestry, and disaster management; and on technical solutions, education and capacity development, although some do include ecosystem response measures (Madzwamuse, 2010; Mamouda, 2011; Pramova et al, 2012). Constraints identified with the NAPAs and some of the NCCRS include a relatively narrow focus on biophysical vulnerabilities and sectoral or project approaches, which limits an integrated cross-sectoral adaptation response; inadequate inclusion of the adaptation needs of vulnerable societal sectors; no or little inclusion of energy adaptation; de-linkage from economic planning and poverty reduction processes; and little facilitation of investment funding - only a small percentage of the NAPA activities have been funded (Romero Gonzalez et al, 2011; Mamouda, 2011; Prowse et al, 2009; Madzwamuse, 2010).

Subsequent to the NAPAs and early experience with the NCCRS, there is some evidence of evolution to a more integrated, multi-level and multi-sector approach to adaptation planning (medium confidence): Ethiopia's Programme of Adaptation to Climate Change deals with adaptation at sectoral, regional, national and local community levels (Hunde, 2012); Lesotho is developing a coordinated policy framework involving all ministries and stakeholders (Corsi et al., 2012); and cross-sectoral adaptation planning and risk management is occurring through mainstreaming initiatives like the twenty country Africa Adaptation Programme (AAP), initiated in 2008 (UNDP, 2009; UNDP, 2010). Examples of the more programmatic approach of national climate resilient development strategies include Rwanda's National Strategy on Climate Change and Low Carbon Development, under development in 2012, and the Pilot Programmes for Climate Resilience in Niger, Zambia and Mozambique (Climate Investment Fund, 2009). Inter-sectoral climate risk management approaches can be detected in integrated

water resources management, disaster risk reduction, and land use planning initiatives, while studies have highlighted the role of integrated coastal zone management in reducing the vulnerability of coastal towns to climate change and particularly coastal flooding (Koch et al, 2007; Boateng, 2006; Cartwright *et al*., 2008; Awuor *et al*., 2008; Kebede *et al*., 2012; Kebede and Nicholls, 2011). Concerning spatial planning, climate change design principles have been incorporated into existing systematic biodiversity planning to guide land use planning in South Africa (Petersen and Holness, 2011).

Adaptation planning is occurring within efforts to construct enabling national policy environments for adaptation in many countries. Examples include Namibia's National Policy on Climate Change (IIED, 2011b); Zambia's National Climate Change Response Strategy and Policy, and South Africa's Draft National Climate Change Response Green Paper in November 2010. Ten countries were developing new climate change laws or formal policies at the end of 2012, including the proposed National Coastal Adaptation Law in Gabon (Corsi et al., 2012).

Despite this progress in mainstreaming climate risk in policy and planning, significant disconnects still exist at the national level, and implementation of a more integrated adaptation response remains tentative (high confidence) (Koch et al, 2007; Madzwamuse, 2010; Fankhauser and Schmidt-Traub, 2010; Oates et al, 2011; UNDP-UNEP Poverty-Environment Initiative, 2011b). Legislative and policy frameworks for adaptation in southern Africa remain fragmented (IIED, 2011b), as is the case for the region as a whole, where adaptation policy approaches seldom take into account realities in the political and institutional spheres (Naess et al, 2011; Lockwood, 2012). While climate resilience is starting to be mainstreamed into economic planning documents - for example, Zambia's Sixth National Development Plan 2011-2015, and the new Economic and Social Investment Plan in Niger (Corsi et al., 2012) - macro-economic development frameworks in Africa have been found to undercut adaptive capacity of poor people through measures to draw foreign direct investment and promote industrial competitiveness (Madzwamuse, 2010),while poor business environments impede both foreign direct investment and adaptation (Collier et al, 2008). National policies are often at odds with autonomous local adaptation strategies, which can act as a barrier to adaptation, especially where cultural, traditional and context-specific factors are ignored (Stringer et al., 2009; Patt and Schroter, 2008; Dube and Sekhwela, 2008; Hisali et al, 2011). National adaptation planning has placed little attention on integrating forests into programmes and strategies compared to mitigation (Bele et al. 2010; Kalame et al. 2011; Sonwa et al. 2012), despite opportunities for enhancing adaptation through forest governance reforms to improve community access to forest resources (Kalame et al. 2008).

22.4.4.3. Institutional Frameworks for Adaptation

The nature of the adaptation institutions at the global level, both within and outside of the UNFCCC, are of critical importance for Africa's ability to move forward on adaptation (Chapter 14). Regional institutions focused on specific ecosystems rather than on political groupings, such as the Commission of Central African Forests (COMIFAC), present an opportunity to strengthen the institutional framework for adaptation. National frameworks include a number of institutions that cover all aspects of climate change, not just adaptation: most countries have inter-ministerial coordinating bodies and inter-sectoral technical working groups, while an increasing number of countries have established multi-stakeholder co-ordinating bodies, including Kenya, South Africa, Senegal and Tanzania (Harmeling et al, 2011). National institutions for climate finance are being established to manage international and domestic funding and encourage mainstreaming into national plans, including the National Implementing Entities in terms of the Adaptation Fund, and national funds to serve as conduits for all sources of climate change funding (Gomez-Echeverri, 2010; Smith et al, 2011).

Under uncertain climatic futures, hierarchical governance systems that operate within siloes will need to be replaced with more adaptive, integrated, multi-level and flexible governance approaches, and inclusive decision making that can operate successfully across multiple scales – or adaptive governance and co-management (Folke et al., 2005; Olsson et al., 2006; Koch et al, 2007; Berkes, 2009; Pahl-Wostl, 2009; Armitage & Plummer, 2010; Bunce et al., 2010a; Plummer, 2012). Despite some progress with developing the institutional framework for governing adaptation, there are significant problems with both transversal and vertical coordination, including institutional duplication with other inter-sectoral platforms, such as those set up for disaster risk reduction; while in fragile states, institutions for reducing climate risk and promoting adaptation may be extremely weak or almost non-existent

(Bettencourt, 2011; Belay Simane et al, 2012; Sietz et al, 2011; Hartmann and Sugulle, 2009). Facilitating institutional linkages and coordinating responses across all boundaries of government, private sector and civil society would enhance adaptive capacity (Brown et al., 2010).

22.4.4.4. Sub-National Adaptation Governance

Since AR4, there has been additional effort on adaptation planning at sub-national and local levels in African countries, but adaptation strategies at provincial and municipal levels are mostly still under development, with many local governments lacking the capacity and resources for the necessary decentralised adaptation response (high confidence). Provinces or states in some countries have developed policies and strategies on climate change: for example, in Nigeria, Delta State developed a Climate Change Policy in 2010, and Lagos State an Adaptation Strategy in 2012 (BNRCC, 2012). Adaptation has been integrated into five district development plans in Ghana, and Morocco's government has approved four communal climate change resilience plans (Corsi et al., 2012). Promising approaches include sub-national strategies that integrate adaptation and mitigation in a low-carbon climate resilient development approach, as is being done in Delta State in Nigeria, Mbale Region in Uganda, and several regions in Senegal, with similar plans for regions of Kenya, South Africa, Burkina Faso, Ivory Coast, Namibia and Egypt (UNDP, 2011b). In response to the identified institutional weaknesses, capacity development has been implemented in many cities and towns, including initiatives in Lagos, Nigeria, Durban and Cape Town in South Africa: notable examples include Maputo's specialized local government unit to implement climate change response, ecosystem-based adaptation and improved city wetlands; and participatory skills development in integrating community-based disaster risk reduction and climate adaptation into local development planning in Ethiopia (Madzwamuse, 2010; ACCRA, 2012; Broto, Vaesa, et al. 2013).

22.4.4.5. Community-Based Adaptation

Since AR4, there has been considerable progress in Africa in implementing and researching community-based adaptation (high confidence), with broad agreement that support to local-level adaptation is best achieved by starting with existing local adaptive capacity, and incorporating and building upon present coping strategies, including indigenous practices (Archer et al, 2008; Dube & Sekhwela, 2007; Huq, 2011). Some relevant initiatives include the Community-based Adaptation in Africa (CBAA) project, which supported three-year climate change adaptation pilot projects at community level in eight African countries (Sudan, Tanzania, Uganda, Zambia, Malawi, Kenya, Zimbabwe, South Africa), implemented as a learning-by-doing approach; and the Adaptation Learning Program, implemented in Ghana, Niger, Kenya and Mozambique (Care International, 2012). The literature includes a wide range of case studies detailing involvement of local communities in adaptation initiatives and projects facilitated by NGOs and researchers (for example, Leary et al, 2008; CCAA, 2011; Care International, 2012); these and other initiatives have generated process-related lessons (section 22.4.5), with positive assessments of effectiveness in improving adaptive capacity of African communities, local organisations and researchers (Lafontaine et al, 2012). Local adaptation planning using participatory scenario development workshops in Mozambique, Ghana, and Ethiopia has revealed the following priorities for pro-poor adaptation: social protection, services and safety nets; better water and land governance; enhanced water storage and harvesting; better post-harvest services; strengthened civil society and greater involvement in planning; and more attention to urban and peri-urban areas heavily affected by migration of poor people (Bizikova et al, 2010).

22.4.4.6. Adaptation Decisionmaking and Monitoring

Emerging patterns regarding adaptation decision-making in Africa include limited inclusive governance at the national level, while some local level initiatives have achieved greater involvement, including of vulnerable and exposed people, in assessing and choosing adaptation responses (high confidence). Civil society institutions and communities have to date played a limited role in formulation of national adaptation policies and strategies, highlighting the need for governments to widen the political space for citizens and institutions to participate in decision-making, for both effectiveness and to ensure rights are met (Madzwamuse, 2010; Castro et al, 2012).

Building African leadership for climate change may assist with this (Climate Change Adaptation in Africa Programme, 2011; Chandani, 2011; Corsi et al., 2012). A critical issue is how planning and decision making for adaptation uses scientific evidence and projections, while also managing the uncertainties within the projections (Dodman and Carmin, 2011; Conway, 2011). The importance of understanding how local knowledge forms the "knowledge frame" through which scientific forecasts are interpreted has been emphasised (Roncoli *et al*. 2009; Ifejika Speranza *et al*., 2010; Newsham and Thomas, 2011).

The range of tools used in adaptation planning in Africa includes vulnerability assessment using various mapping techniques (section 22.4.5), risk assessment, cost-benefit analysis, cost-effectiveness, multi-criteria analysis, and participatory scenario planning. In Ghana, the Akropong Approach was developed to assess inter-relationships between sectoral adaptation options; multi-criteria analysis was used to evaluate and rank the options in the development of the National Climate Change Adaptation Strategy (Kemp-Benedict and Agyemang-Bonsu, 2008). Cost-benefit analysis was used to inform water management decisions for the Berg River basin in South Africa (Callaway et al, 2008) and in uplands of The Gambia to evaluate increased fertilizer use against adoption of irrigation in cereal cultivation (Njie et al, 2008). Adaptation decision making in the coastal zone in South Africa has encompassed cost benefit analysis decision tools, and modeling and mapping the combined effects of sea level rise and coastal storm surge (Cartwright *et al*., 2008; Mather and Stretch, 2012). Innovative approaches include using participatory scenario planning in Ghana and Kenya (CARE, 2012), and developing an online interactive disaster management decision support system as part of the national adaptation response in Mozambique (Corsi et al., 2012).

Monitoring and assessing adaptation is still in its infancy in Africa, with national coordinating systems for collating data and synthesizing lessons not in place. Local-level monitoring of adaptation actions takes place at the project level: a positive community-based adaptation example in the Koue Bokkeveld, South Africa, approaches monitoring through a participatory action research framework, combined with integrating climate projections, local monitoring of climate variables and collaborative assessment of coping/adaptation actions (Archer et al., 2008).

22.4.5. Experiences with Adaptation Measures in Africa and Lessons Learned

22.4.5.1. Overview

Section 22.4.5 provides a cross-cutting assessment of experience gained in Africa with a range of adaptation approaches, encompassing climate risk reduction measures; processes for participatory learning and knowledge development and sharing; communication, education and training; ecosystem-based measures; and technological and infrastructural approaches; concluding with a discussion of maladaptation.

Common priority sectors across countries for implementing adaptation measures since 2008 include agriculture, food security, forestry, energy, water, and education (Corsi et al., 2012), which reflect a broadening of focus since the AR4. While there has been little planning focus on regional adaptation (Sections 22.4.4.2 and 22.4.4.3), the potential has been recognized for regional approaches to adaptation, such as the West African program on coastline change and adaptation (Niang, 2012) and the Congo Basin Forest and Climate Change Adaptation initiative (Sonwa et al., 2009) to catalyze effective collaboration between African countries (UNFCCC, 2007).

Research has highlighted that no single adaptation strategy exists to meet the needs of all communities and contexts in Africa (high confidence). In recognition of the socioeconomic dimensions of vulnerability (Bauer and Scholz, 2010), the previous focus on technological solutions to directly address specific impacts is now evolving toward a broader view that highlights the importance of social, institutional, policy, knowledge, and informational approaches (African Development Forum, 2010; Chambwera and Anderson, 2011), and on linking the diverse range of adaptation options to the multiple livelihood–vulnerability risks faced by many people in Africa (Tschakert and Dietrich, 2010) . 'Soft path' measures are seen as holding promise for adaptation strategies (Martens et al., 2009).

Attention is increasing on identifying opportunities inherent in the continent's adaptation needs, as well as delineating key success factors for adaptation. A number of studies identify the opportunity inherent in implementing relatively low-cost and simple low-regrets adaptation measures that reduce people's vulnerability to

current climate variability, have multiple developmental benefits, and are likely to reduce vulnerability to longer-term climate change as well (UNFCCC, 2007; Conway and Schipper, 2011; see also Section 22.4.3). Responding to climate change provides an opportunity to enhance awareness that maintaining ecosystem functioning underpins human survival and development in a most fundamental way (Shackleton and Shackleton, 2011), and to motivate for new development trajectories (section 22.4.6). While it is difficult to assess adaptation success, given temporal and spatial scale issues, and local specificities, Osbahr et al. (2010) highlight the role of social networks and institutions, social resilience, and innovation as possible key success factors for adaptation in small-scale farming livelihoods in southern Africa.

The following discussion of adaptation approaches under discrete headings does not imply that these are mutually exclusive – adaptation initiatives usually employ a range of approaches simultaneously.

22.4.5.2. Climate Risk Reduction, Risk Transfer, and Livelihood Diversification

African countries have gained experience in a range of approaches to offset the impacts of natural hazards on individual households, communities, and the wider economy, through the following risk reduction strategies: early warning systems, emerging risk transfer schemes, social safety nets, disaster risk contingency funds and budgeting, livelihood diversification, and migration as an adaptive response (World Bank, 2010; UNISDR, 2011). Figure 22-7 shows an assessment of Africa's present and near term risks and risks at the end of the century for 2 temperatures (2°C and 4°C for 2080-2100), and the role of adaptation in reducing those risks.

[INSERT FIGURE 22-7 HERE
Figure 22-7: Risks for the present (blue line), for the near-term (2°C for 2030-2040) and for the end of the century for 2 temperatures (2°C and 4°C for 2080-2100). Risks are depicted for low adaptation and high adaptation.]

Disaster risk reduction (DRR) platforms are being built at national and local levels (Westgate, 2010), with the synergies between DRR and adaptation to climate change being increasingly recognized in Africa (UNISDR, 2011). At the policy level, the shift toward more proactive risk management can be seen in Ethiopia's updated Disaster Risk Management policy, which also emphasizes decentralized and community-based actions (Hunde, 2012), although Conway and Schipper (2011) find that additional effort is needed for a longer-term vulnerability reduction perspective in disaster management institutions.

Early warning systems (EWS) are gaining prominence as multiple stakeholders strengthen capabilities to assess and monitor risks and warn communities of a potential crisis. The operation of regional systems such as the Permanent Inter-States Committee for Drought Control in the Sahel (CILSS) and the Famine Early Warning System Network (FEWS-NET) are seen as crucial for adaptation (Sissoko et al., 2011) . National, local, and community-based EWS on food and agriculture, such as in Niger, Mauritania, Ethiopia, and Burkina Faso, aim to support an effective response to food, nutritional, and pastoral crises (FAO, 2012; Pantuliano and Wekesa 2008). Some of the recent EWS emphasise a gendered approach, and may incorporate local knowledge systems used for making short-, medium-, and long-term decisions about farming and livestock-keeping, as in Kenya (UNDP, 2011). In the health sector, EWS that have employed weather forecasting to predict disease have also been used for adaptation planning and implementation. For example, conditions expected to lead to an outbreak of Rift Valley fever were predicted and a 2 to 6 week warning provided, prior to the occurrence in the Horn of Africa from December 2006 to May 2007(Ayamba, 2006), and progress has been made in prediction of meningitis and in linking climate/weather variability and extremes to the disease, which will be useful in adaptation planning and implementation (Thomson et al., 2006: Cuevas et al., 2007; Irving et al., 2011).

Local projects often use participatory vulnerability assessment methods in the design of adaptation activities (Van Vliet, 2010; GEF Evaluation Office, 2011), but vulnerability assessment at the local government level is often lacking, and assessments to develop national adaptation plans and strategies have not always been conducted in a participatory fashion (Madzwamuse, 2010). Lessons from vulnerability analysis highlight that the highest exposure and risk do not always correlate with vulnerable ecosystems, socially marginalized groups, and areas with at-risk infrastructure, but may also lie in unexpected segments of the population (Moench, 2011).

Various community-level DRR initiatives have focused on resilience-building activities that highlight the links between strengthening food security and household resilience, and delivery of environmental conservation, asset creation, and infrastructure development objectives and co-benefits (Parry et al., 2009b; UNISDR, 2011; Frankenberger et al., 2012). Food security and nutrition-related safety nets and social protection mechanisms can mutually reinforce each other to enhance disaster risk management and climate adaptation, as is being carried out in the Karamoja Productive Assets Programme in Uganda (Government of Uganda and WFP 2010; WFP, 2011). Initiatives in Kenya, South Africa, Swaziland, and Tanzania have also sought to deploy local and traditional knowledge for the purposes of disaster preparedness and risk management (Galloway Mclean, 2010; Mwaura, 2008). Haan et al. (2012) highlight the need for increased donor commitment to the resilience-building agenda within the framework of DRR, based on lessons from the Somalia 2011 famine.

Implementation of effective national and local instruments to offset the impact of natural hazards in Africa, notably concerning social protection and insurance, has been increased. Social protection, a key element of the African Union social policy framework, can include social transfers (cash or food), minimum standards such as for child labor, and social insurance, and is being used in Ethiopia, Rwanda, Malawi, Mozambique, South Africa, and other countries to buffer against the impacts of shocks and disasters by building assets and increasing household resilience of both chronically and transiently poor people (Brown et al., 2007; Heltberg et al. 2009). Examples of social protection systems aimed at moving beyond repeated relief interventions to address *inter alia* slower onset climate shocks are Ethiopia's Productive Safety Net Program (PSNP), the largest social protection program in Africa (Brown et al., 2007), and Rwanda's Vision 2020 Umurenge Program (VUP). There is evidence that social protection is helping with *ex post* and *ex ante* DRR, and that such systems will be increasingly important as a safety net and for securing livelihoods under increasing climate variability, but less evidence exists for the effectiveness of social protection against the most extreme climatic shocks, which requires adaptive strategies that reduce dependence on climate sensitive livelihood activities (Davies et al., 2009; Wiseman et al., 2009; Pelham et al., 2011; Béné et al., 2012). Social protection initiatives could contribute more to building adaptive capacity if based on improved understanding of the structural causes of poverty, including political interests and institutional dimensions (Brown et al., 2007; Davies et al., 2009; Levine et al., 2011).

A number of different mechanisms are used by communities and individuals to spread risk in the African context: kinship networks; community funds; and disaster relief and insurance, which can provide financial security against extreme events such as droughts, floods, and tropical cyclones, and concurrently reduce poverty and enhance adaptive capacity[8] (Leary et al., 2008; Linnerooth-Bayer et al. 2010; Coe and Stern, 2011). Contingency planning at national and local levels, for example for drought, is an important element of risk reduction processes, although this may be hampered by not being linked to sustainable contingency funds (Lesukat, 2012). In Ethiopia, an integrated national risk management framework is being developed through the Livelihoods, Early Assessment and Protection (LEAP) project, an innovative early warning–early action tool that supports the PSNP, including a US$ 160 million contingency fund, which will promote drought risk management. Recent developments in the insurance sector in Africa include the emergence of index-based insurance contracts (Box 22-1), which pay out not with the actual loss, but with a measurable event that causes loss.

[FOOTNOTE 8: Climate (or disaster) risk financing instruments include contingency funds; agricultural and property (private) insurance; sovereign insurance; reallocation of program expenditures; weather derivatives; and bonds.]

_____ START BOX 22-1 HERE _____

Box 22-1. Experience with Index-Based Weather Insurance in Africa

Malawi's initial experience of dealing with drought risk through index-based weather insurance directly to smallholders appears positive: 892 farmers purchased the insurance in the first trial period, which was bundled with a loan for groundnut production inputs (IRI 2009). In the next year, the pilot expanded, with the addition of maize, taking numbers up to 1,710 farmers and stimulating interest among banks, financiers, and supply chain participants such as processing and trading companies and input suppliers. A pilot insurance project in Ethiopia was designed to

pay claims to the government based on a drought index that uses a time window between observed lack of rain and actual materialization of losses. This allows stakeholders to address threats to food security in ways that prevent the depletion of farmers' productive assets, which reduces the future demand for humanitarian aid by enabling households to produce more food during subsequent seasons (Krishnamurty 2011). Another key innovation in Ethiopia is the insurance for work program that allows cash-poor farmers to work for their insurance premiums by engaging in community-identified disaster risk reduction products, such as soil management and improved irrigation (WFP 2011), which makes insurance affordable to the most marginalized and resource-poor sectors of society.

_____ END BOX 22-1 HERE _____

The challenges associated with current risk reduction strategies include communication challenges related to EWS: conveying useful information in local languages; communicating EWS in remote areas; national-level mistrust of locally collected data, which are perceived to be inflated to leverage more relief resources (Hellmuth et al., 2007; Pantuliano and Wekesa, 2008; Cartwright, 2008b; FAO, 2011); the call for improved user-friendliness of early warning information; and the need for better linkages between early warning, response, and prevention (Haan et al., 2012).

Evidence is increasing that livelihood diversification, long used by African households to cope with climate shocks, can also assist with building resilience for longer term climate change by spreading risk. Over the past 20 years, households in the Sahel have reduced their vulnerability and increased their wealth through livelihood diversification, particularly when diversifying out of agriculture (Mertz et al., 2011). Households may employ a range of strategies, including on-farm diversification or specialization (Sissoko et al., 2011; IIED, 2011a). Motsholapheko et al. (2011) show how livelihood diversification is used as an adaptation to flooding in the Okavango Delta, Botswana, and Badjeck et al. (2010) recommend private and public insurance schemes to help fishing communities rebuild after extreme events, and education and skills upgrading to enable broader choices when fishery activities can no longer be sustained..

While livelihood diversification is an important adaptation strategy, it may replace formerly sustainable practices with livelihood activities that have negative environmental impacts (Section 23.4.5.8). Diversification at the national level is also required, especially where there is dependence on a single cash crop, such as cocoa cultivation in Ghana, which is highly vulnerable to the negative effects of climate change (UNFCCC, 2007).

Rural finance and micro-credit are seen as enabling activities for adaptive response, which are also used by women for resilience-building activities (e.g., as documented in Sudan by Osman-Elasha et al., 2006). Credit and storage systems are instrumental to support families during the lean period, to prevent the sale of assets to buy food when market prices are higher (Romero Gonzalez et al., 2011). Long seen as a fundamental process for most African families to incorporate choice into their risk profile and adapt to climate variability (Goldstone, 2002; Urdal, 2005; Reuveny, 2007; Fox and Hoeshler, 2010), there is evidence in some areas of the increased importance of migration and trade for livelihood strategies, as opposed to subsistence agriculture, as shown by Mertz et al. (2011) for the Sudano-Sahelian region of West Africa. Migration involves complex decision making and often supports adaptation to climate change, and may unlock diverse and innovative responses through the role of migrant social institutions (Scheffran et al., 2011; McLeman and Smit, 2006; Scheffran et al., 2012). However, climate-forced migration can exacerbate environmental degradation (e.g., on the Sahel margins) and accelerate land use changes with potential feedbacks to local climate, which can in return increase vulnerability (citations).

22.4.5.3. Adaptation as a Participatory Learning Process

Since AR4, there has been more focus on the importance of flexible and iterative learning approaches for effective adaptation (medium evidence, medium agreement). Learning approaches under investigation in Africa include action research, participatory adaptation planning, and adaptive management. Due to the variety of intersecting social, environmental, and economic factors that affect societal adaptation, governments, communities, and individuals (Jones et al., 2010; Jones 2011), adaptation is increasingly recognized as a complex process involving multiple linked steps at several scales, rather than a series of simple planned technical interventions (Moser and

Ekstrom 2010). Implementing adaptation as a participatory learning process enables people to adopt a proactive or anticipatory stance to avoid 'learning by shock' (Tschakert and Dietrich, 2010).

A number of adaptation initiatives in Africa emphasize the importance of iterative and experiential learning for a flexible adaptation planning, required to deal with the uncertainty inherent in climate projections, compounded by other sources of flux that affect populations in Africa, and the desirability of adjusting approaches based on lessons learned, through a participatory learning-by-doing or experiential learning modality (Suarez et al., 2008; Koelle and Annecke, undated; Dodman and Carmin, 2011; Huq, 2011). Many studies have highlighted the utility of participatory action research, multi-stakeholder dialogue, and experiential learning for managing uncertainty and leading to the social and behavioral change required for adaptation (e.g., Ziervogel and Opere, 2010; Bizikova et al., 2010); CCAA, 2011; Ebi et al., 2011; Faysse et al., 2012; Thorn, forthcoming). Transdisciplinary approaches are also starting to be adopted, as for example in the urban context (Evans, 2011). Learning approaches for adaptation may involve co-production of knowledge – such as combining local and traditional knowledge with science (Section 22.4.5.4).

Recent analyses highlight the importance of social learning and collective action to promote adaptation, and the need to create safe or enabling spaces for multi-stakeholder civic engagement for the adaptation learning process (UNDP/UNEP Poverty-Environment Initiative, 2011a; Tompkins and Adger, 2003). Based on work in Ghana, Tschakert and Dietrich (2010) propose creating learning spaces for iterative learning-by-doing to promote anticipatory adaptation, drawing together learning and principles from both resilience thinking and action research/learning from a dynamic systems perspective. Plummer (2012) points out the potential for adaptive co-management[9] to develop capacity to deal with change, which is relevant for climate change adaptation. Some experience is being gained on the implications of the strategic adaptive management approach for adaptation in aquatic protected areas in South Africa (Kingsford et al., 2011).

[FOOTNOTE 9: Adaptive co-management is understood as "a process by which institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of learning-by-doing" (Folke et al., 2002).]

Caveats and constraints to viewing adaptation as a participatory learning process include the time and resources required from both local actors and external facilitators, the challenges of multidisciplinary research, the politics of stakeholder participation and the effects of power imbalances, and the need to consider not only the consensus approach but also the role of conflicts (Tschakert and Dietrich 2010; Aylett, 2010; Shankland and Chambote, 2011; Jobbins, 2011; Beardon and Newman, 2011). Learning throughout the adaptation process necessitates additional emphasis on ways of sharing experiences between communities and other stakeholders, both horizontally and vertically (Section 22.4.5.4).

The increased emphasis on the importance of innovation for successful adaptation, in both rural and urban contexts, relates to interventions that employ innovative methods, as well as the innovation role of institutions (Tschakert and Dietrich, 2010; Scheffran et al., 2012; Dodman and Carmin, 2011; Rodima-Taylor, 2012). While relevant, high-quality data is important as a basis for adaptation planning, innovative methods are being used to overcome data gaps, particularly local climatic data and analysis capability (Tschakert and Dietrich, 2010; GEF Evaluation Office, 2011). Scheffran et al. (2012) show the role of institutional innovation triggered by migration in response to climate threats in the western Sahel, in which communities and migrants are seen as active social agents, with migrant social organizations initiating innovations across regions by transferring technology and knowledge, as well as remittances and resources. Innovative indigenous adaptation measures on the part of Niger Delta communities are documented by Nzeadibe et al. (2012).

22.4.5.4. Knowledge Development and Sharing

Since AR4, attention to the importance of knowledge development and sharing for enhancing adaptation responses has increased. Key areas investigated include bridging the gap between scientific knowledge and policy; the potential of local and traditional knowledge for informing climate risk management in Africa; and developing multi-

stakeholder platforms for knowledge sharing, including regional collaboration**.** Recent literature has confirmed the positive role of local and traditional knowledge in building resilience and adaptive capacity, and shaping responses to climatic variability and change in Africa. Despite this utility, many argue that local knowledge should not be reduced to a technical input for adaptation planning processes and science frameworks (Berkes, 2002; Harvey, 2009; Kronik and Verner, 2009).

Because adaptation in most African contexts is autonomous, choosing specific adaptation actions needs to be informed by farmer's perceptions and be supported by accurate climate information, relevant to the scale where decisions are made (Vogel and O'Brien, 2006; Ziervogel et al., 2008; Bryan et al., 2009; Godfrey et al., 2010). Key problems regarding how science can inform decisionmaking and policy are how best to match scientific information, for example about uncertainty of change, with decision needs; how to tailor information to different constituencies; what criteria to use to assess whether or not information is legitimate to influence policy and decisionmaking; and how to support scientists to provide information that is accessible by practitioners (Vogel et al., 2007; Hirsch Hadorn et al., 2008). Institutional innovation is one solution: for example, Nigeria established the Science Committee on Climate Change to develop strategies to bridge the gap between increasing scientific knowledge and policy to support Nigeria's goals of economic transformation (Corsi et al., 2012).

Interest is increasing and information is growing on the potential of local and traditional knowledge for informing climate risk management in Africa, particularly at the community scale, where there may be limited access to, quality of, or ability to use scientific information. The recent report on extreme events and disasters (IPCC, 2012) supports this view, finding high agreement and robust evidence of the positive impacts of integrating indigenous and scientific knowledge for adaptation. Local knowledge continues to play an important role in adaptation to climate variability and change in Africa, helping communities to select the most appropriate adaptive or coping mechanisms (Nyong et al., 2007; Osbahr et al., 2007; Ifejika Speranza et al., 2010; Goulden et al., 2009b; Jalloh and Roy-Macauley, 2011; Newsham and Thomas, 2011). Concerns about the future adequacy of local knowledge to respond to climate impacts within the multi-stressor context include the decline in intergenerational transmission; a perceived decline in the reliability of local indicators for variability and change, as a result of socio-cultural, environmental, and climate changes (Hitchcock 2009; Jennings and Magrath 2009); and challenges of the emerging and anticipated climatic changes seeming to overrun indigenous knowledge and coping mechanisms of farmers (Berkes, 2009; Ifejika Speranza et al., 2010; Jalloh and Roy-Macauley, 2011). Based on analysis of the responses to the Sahel droughts during the 1970s and 1980s, Mortimore (2010) argues that local knowledge systems are more dynamic and robust than what is often acknowledged.

Linking indigenous and conventional climate observations can add value to climate change adaptation within different local communities in Africa (Nyong et al., 2007; Chang'a et al., 2010; Roncoli et al., 2002). In Western Kenya, scientists work with local rainmakers to develop consensus forecasts, developed by harmonizing downscaled seasonal forecasts with traditional predictions, which are then disseminated in local languages by radio and at community events (Guthiga and Newsham, 2011). A key question is the extent to which local observations correspond to scientific records, with some literature pointing to strong agreement (West et al. 2008 in Burkina Faso) while other studies find weaker correlation (Rao et al. 2011; Osbahr et al., 2011).

Evidence is growing of the importance of multi-stakeholder platforms for sharing experiences and developing collaborative adaptation responses. Drawing on a transboundary project in the Congo Basin, Tata et al. (2012) highlight the importance of encouraging and monitoring multi-actor negotiation and collaboration processes in order to infer and mitigate future complexities in the process. In Kenya and Ghana, participatory scenario planning has been used as a multi-stakeholder platform for adaptation dialogue, and has been effective in achieving local ownership of flexible adaptation decisionmaking, including through improved relationships between local actors and meteorologists (CARE, 2012).

Knowledge sharing between the many innovative adaptation management programs and projects in Africa is hampered by the lack of platforms to share knowledge on adaptation practices within and between countries. While knowledge management in adaptation interventions has evolved (AAP, 2012), and includes a number of web-based platforms, more comprehensive and proactive systems for knowledge sharing are needed, including institutionalized platforms at the national level (GEF Evaluation Office, 2011).

There is agreement that culture – shaping social norms, values, and rules including those related to ethnicity, class, gender, health, age, social status, cast, and hierarchy – is of crucial importance for adaptive capacity. Culture is important both as a positive attribute but also as a barrier to successful adaptation at the local level, as well as being important in defining who will lose and who will win from adaptation. However, further research is required in this field, not least because culture is highly heterogeneous within a society or locality (Adger et al., 2007, 2009; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Jones, 2011).

Studies show that integrating cultural components such as stories, myths, and oral history into initiatives to document local and traditional knowledge is a key to better understanding how climate vulnerability and adaptation are framed and experienced (Urquhart, 2009; Ford et al.,.2011; Beardon and Newman, 2011). Nielsen and Reenberg (2010) found that in Northern Burkina Faso, issues of social prestige and cultural identity prevent upper-caste households from engaging in adaptive strategies, such as labor migration, employment with development projects, dry season gardening, and women's income-generation activities. Further, while traditional knowledge may hold significant adaptive and broader social value, it may also be closely guarded or selectively transmitted, limiting women's adaptive capacity in many parts of Africa (Davis, 2010; Roncoli et al., 2009; see also section 22.4.5.9).

Extraction of local and traditional knowledge from the social context that gives it meaning and legitimacy may expose it to the risk of being misunderstood, misused, or misappropriated (McGregor, 2004). To avoid these pitfalls and realize beneficial synergies of local and scientific knowledge, appropriate and equitable processes of participation and communication between scientists and local people are required (Nyong et al., 2007; Orlove et al., 2010; Crane, 2010).

22.4.5.5. Communication, Education, and Training

Enhanced support for communication, education, and training is required to raise awareness and empower people to understand the manifestations of climate change and for behavioral change. Systemic causes of knowledge gaps have been identified in parliamentarian's understanding of climate threats and responses, such as limited access to parliamentary researchers and even to the internet (IIED, 2011b). There has been additional experience with civil society-driven approaches to advocacy and raising awareness about climate change and the need for adaptation (Reid et al., 2010; CCAA, 2011), with examples including youth ambassadors in Lesotho and civil society organizations in Tanzania (Corsi et al., 2012). Some evidence exists of the effectiveness of children as communicators and advocates for behavioral and policy change for adaptation to climate change (Section 22.4.3).

Capacity development to enhance understanding of climate impacts and adaptation measures has been undertaken by a range of institutions, such as regional and national research institutes, international and national programs and non-governmental organizations, and agencies of the United Nations (UNFCCC, 2007; START, 2011). Training and capacity development components are usually included in most adaptation interventions, sometimes within a gender-sensitive approach, and targeting youth (e.g., Figueiredo and Perkins, 2012). However, progress on inclusion of climate change into formal education is mixed. A number of countries have integrated climate change into educational curricula to increase awareness, while in Nigeria, climate change adaptation is becoming an educational priority (UNFCCC, 2007; Corsi et al., 2012), and this has been pursued through project-level approaches. However, integration of climate change into educational curricula occurs within the relatively low priority given to environmental and sustainable development education in most countries, as documented for the SADC (Mukute et al., 2012).

Innovative methods are being used to understand and communicate climate change: photo stories, oral history videos, drama, radio, television, festivals, involvement of youth, the use of participatory video in communicating community-based adaptation within and between communities, and influencing policy decisions. Harvey (2011) showed the usefulness of public education using community radio, video, and participation approaches to provide information about community-level adaptation initiatives, while Chikapa (2012) found that radio, cinema, and vernacular publications were critically important in enhancing community-based adaptation to climate change in Malawi. In Malawi and Mozambique, video and participatory approaches increased the accessibility of health risk

management to local decisionmakers (Suarez et al., 2008). The role of the media in communication and awareness raising has been highlighted, including through a media capacity building project across 20 countries (Corsi et al., 2012).

Considerable effort is still required to raise awareness of the diverse range of stakeholders at all levels on the different aspects of climate change (Niang, 2007; Simane et al., 2012). Better evidence-based communication processes will enhance awareness of climate change and available responses for both policymakers and community-level development workers. This requires bringing together multiple users and producers of both scientific and local knowledgein a trans-disciplinary process (Hirsch Hadorn et al., 2008; Koné et al., 2012; Ziervogel et al., 2008) to achieve a better understanding of the dimensions of the problem, including its multiple causes and political context (Vogel et al., 2007).

22.4.5.6. Ecosystem Services, Biodiversity, and Natural Resource Management

There is increasing evidence that Africa's longstanding experiences with natural resource management and utilization of biodiversity can be harnessed for effective adaptation responses (high confidence). Relevant experiences include using mobile grazing to deal with both spatial and temporal rainfall variability in the Sahel (Djoudi et al., 2012); reducing the negative impacts of drought and floods on agricultural and livestock-based livelihoods through forest goods and services in Mali, Tanzania, and Zambia (Robledo et al., 2011); ensuring food security and improved livelihoods for indigenous and local communities in West and Central Africa through the rich diversity of plant and animal genetic resources (Jalloh and Roy-Macauley, 2011). Different ecosystem-based responses of value for reducing vulnerability include coastal and inland afforestation, rangeland regeneration, catchment rehabilitation, community forestry, and other forms of community-based natural resource management (CBNRM).

The responsibility placed on local stakeholder institutions for CBNRM, which enables a more flexible response to changing climatic conditions, embodies a supportive approach for local adaptation strategies; CBNRM is also a vehicle for for improving links between ecosystem services and poverty reduction, to enable sustainable adaptation approaches (Shackleton et al., 2010; Chishakwe et al, 2012; Girot et al, 2012). Forests provide valuable safety nets for women: when drought affects agriculture, vulnerable women in many African countries assure their livelihoods by using different forest products such as charcoal and non-timber forest products (Brown, 2011; Paavola, 2008). Based on an analysis of lessons learned in Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe, Chishakwe et al (2012) point out the synergies between CBNRM and adaptation at the community level.

Natural resource management practices that address desertification can also serve as adaptation measures by improving the resilience of ecosystems and people to long-term changes in climate. Two dual-benefit practices that have become widespread in Africa are natural regeneration of local trees (Box 22-2) and water harvesting. Water harvesting practices[10] have increased soil organic matter, improved soil structure, and increased agricultural yields at sites in Burkina Faso, Mali, Niger, and elsewhere, and are used by 60% of farmers in one area of Burkina Faso (Fatondji et al., 2009; Vohland and Barry, 2009; Barbier et al., 2009; Larwanou and Saadou, 2011). Although these and other practices serve as adaptations to climate change, revenue generation and other concerns may outweigh climate change as a motivating factor in their adoption (Nielsen and Reenberg, 2010; Mertz et al., 2009). While destocking of livestock during drought periods may also address desertification and adaptation, the lack of individual incentives to destock and other cultural barriers inhibit their widespread adoption in the Sahel (Hein et al., 2009; Nielsen and Reenberg, 2010).

[FOOTNOTE 10: Water harvesting refers to a collection of traditional practices in which farmers use small planting pits, half-moon berms, rock bunds along contours, and other structures to capture runoff from episodic rain events (Kandji et al., 2006).]

_____ START BOX 22-2 HERE _____

Box 22-2. African Success Story: Integrating Trees into Annual Cropping Systems

Recent success stories from smallholder systems in Africa illustrate the potential for transforming degraded agricultural landscapes into more productive, sustainable, and resilient systems through the integration of trees into annual cropping systems. Trees in croplands reduce exposure of crops to wind and heavy rainfall, enhance moisture retention and rainwater capture, increase yields of grain crops, and expand livelihoods through production of fruits, animal fodder, and fuelwood. For example, in Zambia and Malawi, an integrated strategy for replenishing soil fertility on degraded lands, which combines planting of nitrogen-fixing *Faidherbia* trees with small doses of mineral fertilizers, has consistently more than doubled yields of maize leading to increased food security and greater income generation (Garrity et al., 2010). In the Sahel, natural regeneration, or the traditional selection and protection of small trees to maturity by farmers and herders has, perhaps for centuries, produced extensive parks of *Acacia albida* (winter thorn) in Senegal (Lericollais, 1989), *Adansonia digitata* (baobab) in West and southern Africa (Sanchez et al., 2011), and *Butyrospermum parkii* (Shea butter) in Burkina Faso (Gijsbers et al., 1994). Recent natural regeneration efforts have increased tree density and species richness at locations in Burkina Faso (Ræbild et al., in press) and Niger (Larwanou and Saadou, 2011), though adoption and success is somewhat dependent on soil type (Haglund et al., 2011; Larwanou and Saadou, 2011). In southern Niger, farmer-managed natural regeneration of *Faidherbia albida* and other field trees, which began in earnest in the late 1980s, has led to large-scale increase in tree cover across 4.8 million ha, and to decreased sensitivity to drought of the production systems, compared to other regions in Niger (Reij et al., 2009; Tougiani et al., 2009; Sendzimir et al., 2011). Devolvement of tree ownership from the state to the farmer catalysed farmer-managed natural regeneration, which has subsequently spread through community-based efforts, including partnerships between farmers and NGOs, improving food security while reducing exposure to climate risks.

_____ END BOX 22-2 HERE _____

Intact ecosystem services and biodiversity are recognized as critical components of successful human adaptation to climate change that may be more effective and incur lower costs than 'hard' or engineered solutions, and are often the first line of defence for poor people in Africa (Abramovitz et al., 2002; Petersen and Holness, 2011; UNDP/UNEP Poverty-Environment Initiative, 2011a; Girot et al, 2012; Pramova et al, 2012; Box 22-2). This understanding provides a compelling reason for linking biodiversity, developmental, and social goals, which is taken up in some NAPA projects that aim to support local livelihoods through ecosystem services provision that explicitly contributes to adaptation; for instance, Djibouti targets mangrove restoration to reduce salt water intrusion and coastal production losses due to climate hazards (Pramova et al., 2012).

Differentiation in the literature is growing, particularly in the field of integrated water resources management, between 'hard path' and 'soft path' approaches to adaptation (Sovacool, 2011; Kundzewicz, 2011), with 'soft path' approaches – for example, using intact wetlands for flood risk management, sometimes equated with 'low regrets' approaches to adaptation, as contrasted with 'hard path' approaches like embankments and dams for flood control (International Rivers Network, 2007; Kundzewicz, 2011). While ecosystem-based adaptation (EbA) is an emerging global concept, ecosystem-based strategies are not new in many African local contexts (Figure 22-8). There has been additional experience in Africa with flood risk management as an adaptive response, based on the protection of natural infrastructure such as forests in watersheds and on floodplains, more efficient resource use, better power and water sector planning, decentralized technologies such as rainwater harvesting, and power generation from geothermal, wind, solar, and sustainable biomass sources, as well as small and unconventional hydropower technologies (e.g., kinetic 'free-flow' turbines and wave and tidal power) (citations).

[INSERT FIGURE 22-8 HERE
Figure 22-8: Ecosystem-based adaptation - Farmer Managed Natural Regeneration (FMNR): Benefits of ecosystem management for livelihoods and resilience (Garrity et al. 2010; Haglund et al. 2011; Reij et al. 2009; Sendzimir et al. 2011).]

Despite the evidence from studies cited in this section, scaling-up to prioritize ecosystem responses and EbA in plans and policy has been slow. Additional efforts will be required for a broad understanding that EbA is an integral component of the developmental agenda, rather than a competing 'green' agenda. Adaptive environmental governance represents one of the future challenges for the implementation of EbA strategies in Africa, together with sustainable use of resources, secure access to meet needs under climate change, and strong local institutions to enable this (Robledo et al., 2011). Ecosystem-based adaptation could be an important approach to consider for the globally significant Congo Basin forests, particularly given the predominance of REDD+ approaches for this region that risk neglecting adaptation responses (Somorin et al., 2012; Sonwa et al., 2012).

22.4.5.7. Technological and Infrastructural Adaptation Responses

Since AR4, experience has been gained on technological and infrastructural adaptation, with an emphasis on options being used in agricultural and water management responses, and for climate-proofing infrastructure, which has encompassed construction of submersible roads, raising homesteads, retrofitting or designing buildings, and building sea and flood defenses.

Evidence has increased since the AR4 that farmers are changing their production practices in response to increased food security risks linked to climate change and variability. Examples include planting cereal crop varieties that are better suited to shorter and more variable growing seasons (Akullo and Kanzikwera, 2007, Laube et al., 2012; Thomas et al., 2007; Yaro, 2010; Yesuf et al., 2008), constructing bunds to more effectively capture rainwater and reduce soil erosion (Nyssen et al., 2007; Reij et al., 2009; Thomas et al., 2007), reduced tillage practices and crop residue management to more effectively bridge dry spells (Marongwe, 2011; Ngigi et.al., 2006), and adjusting planting dates to match shifts in the timing of rainfall (Abou-Hadid, 2006; Vincent et al., 2011).

Conservation agriculture has good potential to both bolster food production and enable better management of climate risks (Kassam et al., 2012; Syampungani et al., 2010; Thierfelder and Wall, 2010; Thomas, 2008; Verschot et al., 2007). Such practices, which include conservation/zero tillage, soil incorporation of crop residues and green manures, building of stone bunds, agroforestry, and afforestation/reforestation of croplands, reduce runoff and protect soils from erosion, increase rainwater capture and soil water-holding capacity, replenish soil fertility, and increase carbon storage in agricultural landscapes.

Expansion of irrigation in sub-Saharan Africa holds significant potential for spurring growth in the agricultural sector while also better managing water deficiency risks associated with climate change (Dillon, 2011; You et al., 2011). Embedding irrigation expansion within systems-level planning that considers the multi-stressor context in which irrigation expansion is occurring can help to ensure that efforts to promote irrigation can be sustained and do not instead generate a new set of hurdles for producers or engender conflict (Burney and Naylor, 2012; Laube et al., 2012; van de Giesen et al., 2010). Suitable approaches to expand irrigation in Africa include the use of low-pressure drip irrigation technologies, which is becoming more widely available, and construction of small reservoirs, both of which can help to foster diversification toward irrigated high-value horticultural crops (Karlberg et al., 2007; Woltering et al., 2011; Biazin et al., 2011;). Adapting agricultural water management to increased drought risk and changes in rainfall patterns requires a strategic approach that encompasses overall water use efficiency for both rainfed and irrigated production (Weiβet al., 2009), embeds irrigation expansion efforts within a larger rural development context that includes increased access to agricultural inputs and markets (Burney and Naylor, 2012; You et al., 2011), and that involves an integrated suite of options (e.g., plant breeding and improved pest and disease and soil fertility management, and *in situ* rainwater harvesting) to increase water productivity (Biazin et al., 2011; Passioura, 2006).

Experience has been gained since the AR4 on adaptation of infrastructure (transportation, buildings, food storage, coastal), with evidence that this can sometimes be achieved at low cost, and additional implementation of soft measures such as building codes and zone planning. Examples of adaptation actions for road and transportation infrastructure include submersible roads in Madagascar and building dikes to avoid flooding in Djibouti (UNFCCC, 2007; Urquhart, 2009). Infrastructural climate change impact assessments and enhanced construction and infrastructural standards - such as raising foundations of buildings, strengthening roads, and increasing storm water

drainage capacity - are steps to safeguard buildings in vulnerable locations or with inadequate construction (UN-Habitat and UNEP, 2010; Mosha, 2011; Corsi et al., 2012). Mainstreaming adaptation into infrastructure development can be achieved at low cost, as has been shown for flood-prone roads in Mozambique (Halsnæs and and Trarup, 2009). Softer measures, such as building codes and zone planning are being implemented and are needed to complement and/or provide strategic guidance for hard infrastructural climate proofing, for example, the adoption of cyclone-resistant standards for public buildings in Madagascar (AfDB, 2011). Research in Durban (Naidu et al., 2006) and in the city of Umhlathuze (Zitholele Consulting, 2009) proposed the integration of climate change and especially those changes affecting the coastline into urban development plans, and recognized that the best option for adaptation in the coastal zone is not to combat coastal erosion in the long term, but rather to allow progression of the natural processes.

The potential for adaptation to reduce the risks associated with sea level rise is estimated at 10- to 27- fold, with adaptation costs lower than the economic and social damages expected if nothing is done (Kebede et al., 2010). For example, in Tanzania, the total costs of adaptation to sea level rise are estimated to be between US$ 25 and 62 million per year by 2030 (Figure 22-9).

[INSERT FIGURE 22-9 HERE
Figure 22-9: Total costs of adaptation per year from 2000 to 2100 for Tanzania (including beach nourishment and sea and river dikes) Source: Kebede et al., 2010.]

Reducing post-harvest losses through improved food storage, food preservation, greater access to processing facilities, and improved systems of transportation to markets are important means to enhance food security (Brown et al., 2009; Codjoe and Owusu 2011; Godfray et al., 2010). Low cost farm-level storage options, such as metal silos (Tefera et al., 2011), and triple-sealed plastic bags (Baoua et al., 2012) are effective for reducing post-harvest losses from pests and pathogens. Better storage allows farmers greater flexibility in when they sell their grain, with related income benefits (Brown et al., 2009), and reduces post-harvest infection of grain by aflatoxins, which is widespread in Africa and increases with drought stress and high humidity during storage (Shephard, 2008; Cotty and Jaime-Garcia, 2007).

22.4.5.8. Maladaptation Risks

The literature increasingly highlights the need, when designing development or adaptation research, policies and initiatives, to adopt a longer-term view and to consider the multi-stressor context in which people live, in order to avoid maladaptation, or outcomes that may serve short-term goals but come with future costs to society. The short-term nature of policy and other interventions, especially if they favor economic growth and modernization over resilience and human security, may themselves act as stressors or allow people to only react to short-term climate variability (Bryan et al., 2009; Brooks et al., 2009; Bunce et al., 2010a; Levine et al, 2011). The political context can also undermine autonomous adaptation and lead to maladaptation; for instance, Smucker and Wisner (2008) found that political and economic changes in Kenya meant that farmers could no longer use traditional strategies for coping with climatic shocks and stressors, with the poorest increasingly having to resort to coping strategies that undermined their long-term livelihood security, such as more intensive grazing of livestock and shorter crop rotations. In a case from the Simiyu wetlands in Tanzania, Hamisi et al. (2012) find that coping and reactive adaptation strategies may lead to maladaptation – for instance, through negative impacts on natural vegetation because of increased intensity of farming in wetter parts of the floodplain, where farmers have moved to exploit the higher soil water content.

Some diversification strategies, such as charcoal production and artisanal mining, may increase risk through promoting ecological change and the loss of ecosystem services to fall back on (Paavola, 2008; Adger et al, 2011; Shackleton and Shackleton, 2012). Studies also highlight risks that traditional adaptive pastoralism systems may be replaced by maladaptive activities. For example, charcoal burning has become a major source of income for 70% of poor and middle-income pastoralists in some areas of Somaliland, with resultant deforestation (Hartmann and Sugulle, 2009).

Another example of maladaptation provided in the literature is the long-term hydro-dependency risks and threats to ecosystem health and community resilience as a result of increased dam building in Africa, which may be underpinned by policies of multi-lateral donors (add citations; Jones et al, 2012). Additional substantive review of such international development projects is required to ensure that these do not result in maladaptation.

22.4.6. Barriers and Limits to Adaptation in Africa

A complex web of interacting barriers to local-level adaptation exists that manifests from national to local scales to block adaptation, which includes institutional, political, social, cultural, biophysical, cognitive and behavioral, and gender-related (high confidence). While relatively few studies from Africa have focused specifically on barriers and limits to adaptation, perceived and experienced constraints distilled from the literature encompass the resources needed for adaptation, the factors influencing adaptive capacity, the reasons for not employing particular adaptive strategies or not responding to climate change signals, and the reasons why some groups or individuals adapt but not others (Roncoli et al., 2010; Bryan et al.,. 2011; Nyanga et al., 2011; Ludi et al., 2012).

Institutional barriers can hamper adaptation through elite capture and corruption; poor survival of institutions without social roots; and the lack of attention to the institutional requirements of new technological interventions (Ludiet al., 2012). Tenure security over land and vital assets is widely accepted as being crucial for enabling people to make longer-term and forward-looking decisions in the face of uncertainty, such as changing farming practices, farming systems, or even transforming livelihoods altogether (Brown et al., 2010; Bryan et al., 2009; Romero Gonzalez et al., 2011). In addition to unclear land tenure, legislation forbidding ecosystem use is one of the issues strengthening underlying conflicts over resources in Africa, which will have to be resolved if ecosystems are to contribute to adaptation beyond short-term coping (Robledo et al., 2011). There is also evidence that innovation may be suppressed if the dominant culture disapproves of departure from the 'normal way of doing things' (Ludiet et al., 2012; Jones 2011b).

Characteristics such as wealth, gender, ethnicity, religion, class, caste, or profession can act as social barriers for some to adapt successfully or acquire the required adaptive capacities (Ziervogel et al., 2008; Godfrey et al. 2010; Jones and Boyd, 2011). Based on field research conducted in the Borana area of southern Ethiopia, Debsu (2012) highlights the complex way in which external interventions may affect local and indigenous institutions by strengthening some coping and adaptive mechanisms and weakening others. Restrictive institutions can block attempts to enhance local adaptive capacity by maintaining structural inequities related to gender and ethnic minorities (Jones, 2011b). Constraints faced by women, often through customs and legal barriers, include lack of access to land and natural resources,; lack of credit and input in decisionmaking, lack of ability to take financial risk, lack of confidence, limited access to information and new ideas, and lack of value for women's opinions (McFerson, 2008; Jones 2011b; Peach Brown, 2011, Djoudi and Brockhaus 2011; Ludi et al., 2012; Goh, 2012; Codjoe et al. 2012).

Only a portion of small-scale farmers across Africa is able to adapt to perceived climatic changes, while others are restricted by a suite of overlapping barriers (high agreement, robust evidence). Constraints identified in Kenya, South Africa, Ethiopia, Zimbabwe, Zambia, and Ghana included poverty and a lack of cash or credit (financial barriers); lack of access to water and land, poor soil quality, land fragmentation, poor roads, and pests and diseases (biophysical and infrastructural barriers); lack of access to inputs, shortage of labor, poor quality of seed and inputs attributed to a lack of quality controls by government and corrupt business practices by traders, lack of tenure, and poor market access (institutional, technological, and political barriers); and finally a lack of information on agroforestry/afforestation, different crop varieties, climate change predictions and weather, and adaptation strategies (informational barriers) (Nhemachena and Hassan, 2008; Bryan et al. 2009, 2011; Barbier et al., 2009; Clover and Eriksen, 2009; Deressa et al., 2009; Roncoli et al., 2010; Mandeleni and Anim, 2011; Nyanga et al.,2011).

Recognition is increasing that understanding psychological factors such as mindsets and risk perceptions is crucial for supporting adaptation (Jones, 2011b; Patt and Schroter, 2008; Grothman and Patt, 2005). Cognitive barriers to adaptation include alternative explanations of extreme events and weather such as

religion (God's will), the ancestors, and witchcraft, or seeing these changes as out of people's own control (Artur and Hilhorst, 2012; Mubaya et al. 2012, Jones 2011b). Perceptions studies from Africa do show that most rural farmers perceive changes in weather patterns and acknowledge the associated risks, although the cause of the changes are not always known or are attributed to supernatural forces (Mandleni and Anim, 2011; Roncoli et al., 2010; Byran et al., 2009).

Climate uncertainty, high levels of variability, lack of access to appropriate real-time and future climate information, and poor predictive capacity at a local scale are commonly cited barriers to adaptation from the individual to national level (Repetto, 2008; Mather and Stretch, 2012; Jones, 2011b). Despite the cultural and psychological barriers noted above, several studies have shown that farmers with access to weather information are more likely to be aware of changes and to make adjustments accordingly (Mubaya et al., 2012). Dinku et al. (2011) point out that the current monitoring system is not sufficient for supporting sustainable development, being oriented more toward meteorology than climate, and more toward global interests and the presumed needs of government sectoral managers than the needs of local communities.

At a policy level, studies have detected political, institutional, and discursive barriers to adaptation. Adaptation options in southern Africa have been blocked by political and institutional inefficiencies, lack of prioritization of climate change, and the dominance of other discourses, such as the mitigation discourse in South Africa and short-term disaster-focused views of climate variability (Madzwamuse, 2010; Bele et al., 2011; Berrang-Ford et al., 2011; Chevalier, 2011; Conway and Schipper, 2011; Toteng, 2011; Kalame et al., 2011, Toteng, 2011; Leck et al., 2011). Lack of local participation in policy formulation, the neglect of social and cultural context, and the inadvertent undermining of local coping and adaptive strategies have also been identified by several commentators as barriers to appropriate national policies and frameworks that would support local-level adaptation (e.g., Brockhaus and Djoudi, 2008; Bele et al., 2011; Chevalier, 2011).

Many of these constraints to adaptation are well entrenched and will be far from easy to overcome; some may act as limits to adaptation for particular social groups. Biophysical barriers to adaptation in the arid areas could present as limits for more vulnerable groups if current climate change trends continue (Leary et al., 2007; Sallu et al., 2010; Roncoli et al., 2010). Traditional and autonomous adaptation strategies, particularly in the drylands, have been constrained by social-ecological change and drivers such as population growth, land privatization, land degradation, widespread poverty, HIV/AIDS, poorly conceived policies and modernization, and erosion of traditional knowledge to the extent that it is difficult or no longer possible to respond to climate variability and risk in ways that people did in the past (Leary et al., 2007; UNCCD et al., 2009; Dabi et al., 2008; Paavola, 2008; Smucker and Wisner, 2008; Conway, 2009; Clover and Eriksen, 2009; Bunce et al., 2010b; Jones, 2011b; Quinn et al., 2011). As a result of these multiple stressors working together, the number of response options has decreased and traditional coping strategies are no longer sufficient (Dube and Sekhwela, 2008). Increasingly, people are reporting obstacles to mobility, past collective practices, use of indigenous knowledge and diversification activities that hinder their ability to adapt. Studies have shown that most autonomous adaptation usually involves minor adjustments to current practices (e.g., changes in planting decisions); there are simply too many barriers to implementing substantial changes that require investment (e.g., agroforestry and irrigation) (Bryan et al., 2011). Such adaptation strategies require government and private sector/NGO support, without which many poor groups in Africa may face real limits to adaptation.

These findings highlight the need for transformational change in situations where high levels of vulnerability and low adaptive capacity detract from the possibility for systems to adapt sustainably. This is in agreement with the Special Report on Extreme Events, which additionally found high agreement and robust evidence for a needed spectrum of actions ranging from incremental steps to transformational changes in order to reduce climate risks (IPCC, 2012). In support of such solutions, Moench (2011) has called for distilling common principles for building adaptive capacity at different stages, and adaptive management and learning are seen as critical approaches for facilitating transformation (Section 22.4.5.3; IPCC, 2012).

22.5. Case Studies

22.5.1. Climate Change Impacts on Kilimanjaro

Changing weather conditions, large-scale habitat conversion, agricultural intensification, and rapid human population growth have reached a critical stage at Kilimanjaro (Sala *et al*., 2000; Jetz *et al*., 2007; Lovett and Hemp, 2010). Decreasing precipitation is the main driver of increasing forest fires in combination with illegal logging activities affecting, for example, fog water-collecting capacity and with this, the water balance of the whole mountain. This endangers its function as the water tower for northern Tanzania, with potential to affect 10 million people. The problem is exacerbated by an increase in local population density (10 times in 90 years to over 1 million in 2002). Based on current global climate scenarios, Kilimanjaro's ecosystems will be subject to significant further climate warming and shifts in precipitation patterns (McDonald *et al*., 2005; Huntingford *et al*., 2005; Christensen *et al*., 2007), causing a dangerous combination of decreasing adaptive capacity of many of the systems and increasing threats.

Kilimanjaro's glaciers have lost over 80% of their extent since 1912 (Thompson *et al*., 2002; Cullen *et al*., 2006) and annual precipitation has decreased by over 30% (Hemp, 2005). This declining trend in precipitation and humidity rather than increasing temperature is increasingly held responsible for the retreat of glaciers since 1880 (Kaser *et al*., 2004; Mölg *et al*., 2008; Mölg *et al*., 2009a; Mölg *et al*., 2009b; Kaser *et al*., 2010). Since 1848, when Rebmann first drew the world's attention to the presence, so close to the equator, of glaciers on Kilimanjaro, this ice-capped dome in the hot African sun has not only intrigued scientists and writers but also a large number of tourists. Today, the Kilimanjaro National Park (KINAPA) is a major attraction, generating more foreign currency earnings for Tanzania than any other national park (Hemp *et al*., in press). Since the park was established in 1972, the number of visitors to KINAPA has increased five-fold (Hemp *et al*., in press). Most visitors are intent on reaching the summit of Kibo, known as Uhuru Peak, the highest point in Africa. Kilimanjaro will undoubtedly lose part of its beauty once all its glaciers have disappeared, marking the final chapter in an important paleoclimatic archive (Thompson *et al*., 2002; Hemp *et al*., in press).

Changes in local climatic conditions are triggered not only by large-scale effects (such as ocean circulation and dust–aerosol interactions), but also by regional orographic effects (Mölg *et al*., 2009a) and land use feedback effects (e.g., Christensen et al., (2007); Pepin et al., (2010); Mölg et al., (2012)).

Impact

Fires: Loss of natural habitats due to land cover changes and fires is most severe in the foothills of Kilimanjaro. For 10,000 years, fires occurred with various intensities on Kilimanjaro, as suggested by old charcoal horizons in the soil (Hemp and Beck, 2001; Verschuren *et al*., 2009; Zech *et al*., 2011; Schüler *et al*., 2012). However, due to a drier and warmer climate and higher anthropogenic impacts, fires have played an increasingly destructive role in the forests of Kilimanjaro during the last 100 years but in particular over the last three decades. During this period Kilimanjaro has lost about 150 km^2 (nearly 15%) of high-altitude forests, and the upper closed forest line dropped by 900 m (Hemp, 2005; Hemp, 2006a; Hemp, 2009). A high frequency of fires in the upper regions has caused typical alpine *Helichrysum* heath to extend downslope, replacing subalpine forests (Körner, 2003; Pauli *et al*., 2012). In addition, losses due to clear cutting of lower elevation forests amount to 450 km^2 since 1929 (i.e., Kilimanjaro lost about 40% of its forests; Hemp(2006b); Hemp et al., (in press)). An increase in the migration of elephants from the Amboseli ecosystem via the so-called Kitendeni Corridor into the forests of Kilimanjaro due to rising temperatures and other factors like expansion of indigenous communities also have negative consequences on forest cover (impeded forest regeneration and increasing the risk of fire; Hemp et al., (in press)).

The average annual water yield of the entire forest belt is estimated to be about 500 million m^3 (Hemp, 2005). The loss since 1976 of 150 km^2 of cloud forests, which have an important function of fog water collecting in addition to the normal rainwater input, corresponds to an estimated loss of 20 million m^3 of fog water per year (Hemp, 2005). The Pangani River, one of Tanzania's largest rivers, provides water for the hydro plants of Nyumba ya Mungu (8 MW), Hale (17 MW) and Pangani Falls (66 MW), which together generate some 20 % of Tanzania's total electricity output (Hemp *et al*., in press). A water shortage during dry periods would increase the incidence of power cuts, which even now are severely inhibiting economic growth. Fishing in the Nyumba ya Mungu dam yields a catch of

about 4,000 tonnes annually. Water from the Pangani River underpins the large-scale South-East Moshi rice scheme. The southern slopes of Kilimanjaro also provide the water that feeds the Arusha Chini sugarcane plantations of the Tanganyika Planting Company. In Kenya, the Amboseli ecosystem – including the wetlands of Ol Tukai and Kimana, which support Masai pastoralists and abundant wildlife – depends for its survival on Kilimanjaro's water catchments (Hemp *et al*., in press). The traditional Chagga home gardens, covering an area of about 1,000 km^2, represent a special type of coffee–banana agro-forestry that are also dependent on runoff from the montane forest and are now limited to a lowland field where maize, beans, and sunflower are grown to ensure food security (Hemp, 2006c; Liniger *et al*., 2011).

Striking examples for an upward movement of organisms on Kilimanjaro can be found among the grasshopper fauna. In contrast to alpine flora, savanna grasshoppers are spreading from lower elevations to the sub-montane, montane, and even afro-alpine zone due to anthropogenic opening of the closed forest and a warmer microclimate (Figure 22-10; Hemp and Hemp, (2008)).

[INSERT FIGURE 22-10 HERE
Figure 22-10: Upward movement of grasshoppers and bushcrickets at Kilimanjaro. Left circles giving numbers of species which are typical for this zone; right circles giving numbers of species that are additionally found to the typical species of the respective zone, arrows indicating area from which they migrated upwards. Yellow: openland forms, green: forest forms; blue: afroalpine forms. A: colline lowland savanna area, B: submontane and lower montane zone, C: montane zone, D: (sub) alpine zone. Source: Hemp and Hemp, 2008).]

22.5.2. Coastal Zones and Urbanization

Case Studies – Lagos, Dakar, Saint Louis, and Beira

Coastal cities, Africa's most developed urban areas, host 11.5% of the total urban population (UN-Habitat, 2008b). Lagos, Nigeria; Dakar; and Saint Louis, Senegal, all in the low-lying coastal zone of West Africa, as well as Beira, Mozambique, exemplify the state of Africa's coastal cities that are naturally vulnerable to flood hazards from climate change and sea level rise by reason of their location. Moreover, rapid urbanization in these cities has caused migration of large numbers of people into slum or informal communities, often located in flood-prone and risky areas. For instance, between 1984 and 1992, migration resulted in an average increase of 91% in Beira's population, where 75% of the buildings are located in low-lying areas and most immigrants reside in unplanned settlements (Kusangaya, no date). In Saint Louis, the urban poor settle in watersheds and valley bottoms, altering drainage patterns and destabilizing slopes (Diagne, 2007). Similarly, in the Yeumbeul district in the north of Dakar, flood risk is high due to the occupation of depressions by the urban poor that are normally occupied by streams and natural vegetation (Mbow *et al*., 2008). In Lagos, large sections of poor urban coastal communities have been built on land reclaimed by sand infill, which cannot support solid structures (Adelekan, 2010).

Changes in the intensity and pattern of rain storms, land use changes, and subsequent changes in the hydrological fluxes of the urban watershed associated with urban growth, compounded by inadequate or lack of drainage infrastructure, poor urban planning, and poor development control have consequently increased flood risks in these cities (Mbow *et al*., 2008; Adelekan, 2010). In coastal Lagos, significant wetland loss of 38 to 100% was reported in four coastal local government areas between 1986 and 2006 (Taiwo, 2009). Okude and Ademiluyi (2006) showed that developed land comprising residential, industrial, commercial, transportation, and other uses increased from 85.4 km^2 (43.36%) to 111.9 km^2 (56.8%) between 1986 and 2002. Natural vegetation cover, including mangrove and swamp thicket, was also reduced from 59.2 km^2 (30.1%) to 38.3 km^2 (19.4%). In Beira, dryland vegetated areas (3.55 %) were converted to built-up areas followed by alteration of permanently waterlogged areas (1.53%) and finally bare surfaces (0.54%) between 1999 and 2010 (Kusangaya, no date). Urbanization processes and drivers are therefore the strongest cause of floods in Dakar, Lagos, and Saint Louis (Diagne, 2007; Mbow *et al*., 2008; Adelekan, 2010).

Most African coastal cities have limited capacity and infrastructure to cope with the impacts of climate change and sea level rise. Lagos provides a case study of the possible impacts of trends in precipitation behavior in a vulnerable

urban setting. Analyses of rainstorms for Lagos Island from 1971 to 2005 show that in latter years (1996–2005), heavier rainstorms resulting in flooding were recorded. While mean annual rainfall is similar (1,697.8 mm for 1971–1995 and 1,647.3 mm for 1996–2005), fewer rain days were recorded during the latter 10-year period, indicating that rainstorms were much heavier than those of the earlier period and resulted in more flooding (Adelekan, 2010). The range of impacts experienced in affected communities includes damage to roads, flooding of houses, and disruption of movement. Although the severity of impacts varies within communities, the functioning of affected communities and those of its members are affected (Adelekan, 2010). The worsened environmental conditions arising from flood events contribute to the prevalence of waterborne diseases, hepatitis, intestinal diseases, and malaria in poor urban communities. Douglas et al. (2008) also noted the impact of floods on child health in the poor urban communities of Iwaya/Makoko in Lagos. About 91% of households in affected poor urban communities made regular visits to health centers because of ill health, and incurred increased medical expenses and income loss due to inability to work as a result of illness.

Residents of the Makoko community who had benefited from an improved drainage system experienced less flooding than areas where the drainage system was poor (Douglas *et al.*, 2008; Adelekan, 2010). Furthermore, potable water shortages, due to water pollution and damage to water pipes following flood events and cleaning and repair costs, were also experienced by households affected by floods.

At the individual level, flooding of homes and communities deters social interactions as friends and family cannot visit. The nutritional status of members of flood-affected households is also affected as the floods result in loss of food items and scarcity of food. In terms of economic and livelihood activities, over 90% of respondents in the four communities indicated that flood events denied them of job opportunities or hindered their economic activities. Restrictions on economic activities as a result of floods make poor urban dwellers highly vulnerable as the majority depends on wages earned from daily work.

22.5.3. Case Study on Migration

[to be added]

22.6. New Emerging Issues

22.6.1. Integrated Adaptation / Mitigation Approaches

Since AR4, the literature has increasingly recognized that integrated adaptation–mitigation responses need to be implemented within a pro-poor orientation that leverages developmental benefits. Relevant experience gained in Africa on integrated adaptation–mitigation responses encompasses some participation of farmers and local communities in carbon offset systems, increasing the use of technologies that can promote adaptation and mitigation, such as agroforestry and farmer-assisted tree regeneration, emerging policy response within the context of Green Economy discussions and enhanced utilization of renewable energy resources. The recognition that adaptation and mitigation should not be viewed as tradeoffs, but rather as complementary elements of the global response to climate change, is gaining traction in Africa (Nyong *et al.*, 2007; Goklany, 2007; Woodfine, 2009; UNCCD et al., 2009; Milder et al., 2011). Many adaptation activities can contribute significantly to mitigation, provided the expected synergies are capitalized on (Jalloh and Roy-Macauley, 2011).

While the suitability of on- and off-farm techniques for an integrated adaptation-mitigation response depends on local physical conditions as well as political and institutional factors, the literature highlights that sustainable land management techniques particularly beneficial for an integrated response in Africa include agroforestry, including through farmer-managed natural regeneration and conservation agriculture (Woodfine, 2009; Milder *et al.*, 2011; Mutonyi and Fungo, 2011). An emerging area is multiple-benefit initiatives that aim to reduce poverty, promote adaptation through restoring local ecosystems, and deliver benefits from carbon markets. An example is a community-based project in Humbo, Ethiopia, which is facilitating adaptation and generating temporary certified emissions reductions under the Clean Development Mechanism (Brown *et al.*, 2011). Degraded native forests (2,728

ha) are being restored through farmer-managed natural regeneration, which is found to be low-cost and replicable, with benefits to communities of fodder and firewood within a year, and wild fruits and other non-timber forest products within three years. Local cooperatives and establishing user rights were important enabling conditions.

The important role of local communities in carbon offset systems through community forestry entails land use flexibility (Purdon, 2010). Incorporating trees on-farm could expand the opportunity for participation in carbon offset schemes by smallholder farmers (Kung'u *et al*., 2011). Similarly, the local knowledge of communities can support adaptation and mitigation efforts by drawing from locally appropriate options (Nyong *et al*., 2007; Ogden and Innes, 2009). Integrated approaches are constrained by the lack of supportive policy environments – for example, for conservation agriculture (Milder et al., 2011).

The literature has highlighted the need to pursue integrated adaptation–mitigation approaches in the implementation of REDD+ in Africa, and to use spatial planning to find integrated solutions (Bwango *et al*., 2000; Biesbroek *et al*., 2009). Given the significant contribution to food security and livelihoods of communities in Africa, such as the over 30 million indigenous forest people in the Congo Basin Forest of the Central African Region (Nasi *et al*., 2008; Dudley *et al*., 2008; Somorin *et al*., 2012), adaptation and mitigation are inseparable as climate change responses in forest systems (Guariquata et al., 2007; Nkem *et al*., 2007). However, the use of forests for anticipatory adaptation is limited and predominantly serves for reactive coping (Fisher *et al*., 2010). Discourse among forest actors shows separate policy pathways and inclinations for adaptation and mitigation, with a strong government preference for mitigation while the priority of local communities and community-based actors is for adaptation (Somorin *et al*., 2012). Flexible REDD+ models that include agriculture and adaptation may widen the scope for pro-poor participation (Wertz-Kanounnikoff *et al*., 2011), given food security and adaptation priorities (Nkem *et al*., 2008). This is crucial in avoiding the undesirable tradeoffs in the local adaptive capacities of communities, ecosystems, and nations as well as increased vulnerability of some key sectors like agriculture, with the implementation of REDD+ (Richard *et al*., 2011). Harnessing the full potential and cost-effectiveness of REDD+ depends on the opportunity cost (Kremen *et al*., 2000), which in the case of Africa, links to the tradeoffs in social benefits for local communities as well as support for national development efforts in addressing demands for food, fuel, and fiber that underly the decisionmaking process for land use change (Thomson *et al*., 2010). The additional experience being gained on generating co-benefits for poverty reduction through a five-year project launched in 2010 to investigate synergies between adaptation and mitigation in the Congo Basin, with an emphasis on safeguarding local rights, livelihoods, and traditions, is also relevant (CIFOR, 2011).

There have been a number of studies on identifying the most sustainable regional renewable options for Africa owing to the rapid population growth and increase in industrial activities (Sambo, 2008; Chineke et al., 2010; Chineke and Okoro, 2010; Dike et al., 2011). Options explored include solar, wind, small hydro and improved biomass technologies. Insufficient electricity to meet domestic and industrial needs has been the main driver of the increased focus on exploiting Africa's substantial renewable energy sources, rather than reduction in carbon emissions; however, mitigation and broader environmental reasons are seen as increasingly important (Foster-Pedley et al., 2006; Nwofor et al., 2007). An excellent example of integrating renewable energy generation into a national utility service is available from Mauritius (UNIDO, 2007). The three major barriers to the adoption of renewable energy in Africa are policy/legal, technical and financial barriers; other studies have pointed to the need for enhanced political will and continual lobbying for better policy uptake (Legros et al., 2009; Chineke and Ezike, 2010).

Integrated adaptation–mitigation responses are being considered within the context of the emerging Green Economy discussions at both regional and national levels. African leaders agreed in 2011 to develop an African Green Growth Strategy to guide low-carbon growth and climate resilient development. This will build a shared medium and long-term vision to promote sustainable and low-carbon growth in Africa through a linked adaptation–mitigation approach, with adaptation seen as an urgent priority. At the national level, Ethiopia launched its Climate Resilient Green Economy Facility in 2012 (Corsi *et al*., 2012). Given Africa's ongoing development needs, questions to ask include how adaptation programs can be designed to meet the health, education, and employment needs of communities (African Development Forum, 2010). Similarly, for integrated adaptation and mitigation strategies to be effective and sustainable, it is necessary to understand the synergies and tradeoffs between approaches – for

instance, in the agriculture sector, between various practices for food security and for mitigation of greenhouse gas emissions (Chambwera and Anderson, 2011).

22.6.2. Climate Finance and Management

At the UN climate negotiations in Copenhagen (2009), developed countries pledged to mobilize new and additional financial resources for climate change adaptation and mitigation in developing countries, approaching US$ 30 billion for the period 2010 to 2012, and US$ 100 per annum from 2020 onward (UNFCCC, 2009; UNFCCC, 2011). Historically, less than 20% of the global climate finance was directed to adaptation (Buchner *et al*., 2012). However, in line with increasing international impetus for adaptation (Persson *et al*., 2009) the Parties agreed on providing "adequate, predictable and sustainable financial resources" for adaptation in developing countries, and, within this context, paid special attention to Africa which is considered "particularly vulnerable" to the adverse effects of climate change (UNFCCC, 2009; UNFCCC, 2011).

The need for climate finance led to a proliferation of climate funds (Caravani *et al*., 2010). Adaptation funding currently comes from the domestic budgets of developing countries; bilateral and multilateral development assistance; and funds situated under the UNFCCC (Klein, 2010). The Copenhagen Accord states that it should also come from the private sector (UNFCCC, 2009). The UN secretary general's high-level advisory committee considered private finance necessary to meet the US$ 100 billion per annum target (AGF, 2010). However, doubts remain about how private sector financing can be effectively mobilized and channeled toward adaptation in developing countries (Atteridge, 2011; Naidoo *et al*., 2012). The 2012 Landscape of Climate Finance Report (Buchner *et al*., 2012) stated that private climate finance represents 63% of the total climate finance flows, of which close to two- thirds come from developed countries. It also estimates that mitigation activities attracted US$ 350 billion, mostly related to renewable energy and energy efficiency, while adaptation activities attracted US$ 14 billion.

Approximately 30% of the global distributed adaptation finance went to Africa (Nakhooda *et al*., 2011) and seems to prioritize the continent (Naidoo *et al*., 2012). However, there is general consensus that adaptation funding that is currently delivered does not fulfill demonstrated needs, neither globally (Flåm and Skjærseth, 2009; Denton, 2010) nor in sub-Saharan Africa (Nakhooda *et al*., 2011).

Effective adaptation requires more than sufficient levels of funding. It requires developing country 'readiness,' which includes abilities to plan and access finances; the capacity to deliver adaptation projects and programs, and to monitor, report, and evaluate their effectiveness (Vandeweerd *et al*., 2012). Particularly serious challenges are associated with directing finance to the sectors and people most vulnerable to climate change (Denton, 2010; Nakhooda *et al*., 2011; Pauw *et al*., 2012). Mismanagement and misuse of funds eventually puts at risk the rights of those most vulnerable to the negative effects of climate change. (Transparency International 2011:xxvi). The reasons for the high degree of fund mismanagement with regard to climate finance and adaptation funds are rooted in the level of complexity, uncertainty, and novelty that surrounds many climate issues. Solving these problems would, inter alia, require a focus on longer-term and integrated programs rather than isolated projects; building capacity and institutions in African countries (Nakhooda *et al*., 2011; Pauw *et al*., 2012); identifying priorities, processes, and knowledge needs at the local level (Haites, 2011; Pauw, forthcoming); and, accordingly, developing grassroots projects (Fankhauser and Burton, 2011).

22.7. Research Gaps

Research has a key role to play in providing information for informed decisionmaking at local to national levels (Fankhauser, 1997; Ziervogel *et al*., 2008; Arendse and Crane, 2010). While there is significant activity in African research institutions on adaptation, much African research capacity is spent on foreign-led research that may not relate to national knowledge gaps about climate change (Madzwamuse, 2010), and African research may lack merited policy uptake or global recognition as it is often not published in peer-reviewed literature (Denton *et al*., 2011).

The following data and research gaps have been identified:

- A multi-tiered approach to building institutional and community capacity to respond to climate risk
- Developing methods in vulnerability analysis for capturing the complex interactions in systems across scales
- Frameworks for designing adaptation measures to cope with high levels of uncertainty
- Improved analysis of adaptation technologies to build adaptive capacity and resilience
- Development of African capacity and leadership on climate change, including through strengthening and reorienting climate science and policy institutions to harness synergies for translation of new climate change science into policy and/or decisionmaking tools
- Clements et al. (2011) highlight the importance of investigating potential changes in future economic and social systems under different climate scenarios, in order to increase understanding of the implications of adaptation strategy and planning choices.
- Methodologies and "cyclical learning and decision-support tools to explore anticipatory adaptation in high poverty/high vulnerability contexts" (Tschakert and Dietrich, 2010)
- Integrating a differentiated view of poverty into climate change adaptation and disaster risk reduction in order to more effectively address the root causes of poverty and vulnerability, which can be promoted through further integration of climate change adaptation and disaster risk reduction with social protection.
- Approaches to further develop a more equitable approach to adaptation, including gender equity, human rights- based approaches, and involvement of vulnerable or marginalized groups such as indigenous peoples and children
- How to effectively combine social protection measures to mitigate vulnerability to climate change in different contexts
- Frameworks for identifying and eliminating factors that constrain women's ability to adapt at multiple levels
- Understanding and demonstrating how greater integration of women in decisionmaking could address the inequitable distribution of climate impacts, and could improve adaptive decisionmaking more broadly.
- Understanding the factors that determine the effectiveness of adaptation activities in building resilience and increasing adaptive capacity and the effectiveness of community-based adaptation to climate change and variability.
- Monitoring adaptation
- The ethical and political dimensions of engaging with local and traditional knowledge on climate change adaptation are an important but under-examined issue in Africa. While the concept of indigeneity is debated in Africa, the claims for active participation of marginalized groups in global climate deliberations described above are significant for a wide range of communities in Africa.

Frequently Asked Questions

FAQ 22.1: What is the significance of migration in the context of climate change adaptation in Africa?

Migration was considered as a negative impact in the last decade, but a perception of the potential positive role of migration in climate change adaptation now exists. Even if classical literature tends to ignore the environment as a key driver of migration, new theories on African mobility state that migration is a central issue in the adaptation process and one of the most relevant responses to climate change in Africa, regardless of some negative effects on environmental degradation. As in most regions of the world, environmental change will continue to affect African migration during the coming years. In addition to economic, social, and political drivers, environmental change will play a key role in the migration process. Environmental change will affect livelihoods, making migration a primary answer or the only response. Better management of African migration and displacement is a core issue to avoid humanitarian emergencies and the risk of jeopardizing necessary population mobility due to environmental change.

FAQ 22.2: How could climate change impact food security in Africa?

Food security is comprised of food availability, access, quality, utilization, and acceptability. Strong consensus exists that climate change will have a significantly negative impact on food availability in Africa. This could occur through direct climate impacts on crops and livestock, such as through increased incidence of floods, drought, shifts

in the timing and amount of rainfall, and high temperatures, or indirectly through increased soil erosion brought on by an increased incidence of heavy storms and through increased pest and disease pressure on crops and livestock. The link between climate change and food access is less clear, although there is evidence that climate change impacts in important cereal-producing regions of the world could, along with other factors, contribute to increasing food prices, which impede the ability of the poor and middle class in Africa to purchase food, hence their reduced access to food. The impact of climate change on food quality could occur through increased risk of spoilage of fresh food and pest and pathogen damage to stored foods (cereals, pulses, tubers) under warmer and more humid conditions. Climate change could impact food utilization through increased gastro-intestinal diseases, malaria, and other diseases that reduce the ability of the human body to absorb nutrients from food.

FAQ 22.3: What role does climate change play with regard to violent conflict in Africa?

Wide consensus exists that violent conflicts are based on a variety of interconnected causes, of which the environment is considered to be one, but rarely the most decisive factor. Whether or not the changing climate increases the risk of civil war in Africa remains disputed and there exists a lack of robust findings related thereto. A risk of an increase of violent competition over scarce resources exists with a view to the impacts of climate change on renewable resources such as freshwater and arable land on the one side and population growth on the other. Increased distributional conflicts due to the degradation of natural resources as a result of overexploitation and global warming will arise. The outbreak of armed conflict with climate change as one of various interacting reasons, however, depends on country-specific sociopolitical and economic factors among others.

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Table 22-1: Changes and impacts observed in freshwater lakes of Africa.

Lake	Observed Impacts
Kivu	The upper (below 250 m) water layers warmed up by 0.5°C in the 55-year period between 1937 and 2002 in response to increased air temperatures (?)
Tanganyika	Reductions in phytoplankton biomass have been attributed to an average 0.2°C warming at 1 000 m and 1.3°C of the upper waters during the past century and an average 0.9°C warming across the lake. (Sources: (Sarvala *et al*., 2006a; Sarvala *et al*., 2006b; Stenuite *et al*., 2007; Stenuite *et al*., 2009; Verburg and Hecky, 2009))
Kariba	Warmed up by an average of 1.9°C between 1965 and 2009; thermocline has migrated upward by over 80% from the maximum thermocline depth of 30m reported during the late 1960s, and by over 60% from the maximum thermocline depth of 20m reported during the late 1980s.This warming is associated with an average of 0.34°C per decade increase in air temperature in the Zambezi Valley. (Sources: Ndebele-Murisa, 2012, Magadza, 2010) Consequences Observed: reduced fish production, e.g. exotic Tanganyika sardine, Limnothrissa miodon due to decline in the production of palatable Chlorophyceae, leading to decreased zooplankton production and a consequent decline in fish stocks; reduced phytoplankton biomass and has caused seasonal shifts in phytoplankton seasonality. (Sources: (Magadza, 2011; Ndebele-Murisa *et al*., 2011a; Ndebele-Murisa *et al*., 2011b; Ndebele-Murisa *et al*., 2012))
Turkana	Level has dropped 10m between 1975 and 1992 due to reduced river inflows. (Sources(McGinley, 2008; Thomas and Malala, 2009))
Victoria	Water level has dropped over 1.5m in five years. (Sources: Awange et al., 2008; Hecky et al., 2010) The upper (below 250 m) water layers warmed up by 0.5°C in the 55-year period between 1937 and 2002 and since the 1960s respectively in response to increased air temperatures resulting in sharper water-density gradient at depths below 250 m. (Sources: (Odada *et al*., 2006; Kunz *et al*., 2011))
Malawi	A 60-year (1930 to 2000) temperature record shows that the temperature of deep water above 300 m has increased by 0.78°C. Due to reduced cold-water intrusions associated with milder winters, rainfall and cold river inflow are critical factors in controlling thermal structure and the rate of deep-water recharge in this tropical lake. These findings are corroborated by geochemical records obtained from sediment cores of changes in Lake Malawi over the last 730 years, caused by natural climatic forcing and anthropogenic activities. (Sources: (Branchu *et al*., 2010; Lyons *et al*., 2011))
Chilwa	Dried up nine times in the 20th Century at 10-20 year intervals in relation to patterns in rainfall in the lake basin. (Source: (Njaya *et al*., 2011))

Table 22-2: Land inundated and economic impacts in Cape Town based on a risk assessment (Cartwrigth, 2008a).

Sea level rise scenarios	Land inundated	Economic impacts (for 25 years)
Scenario 1 (+ 2.5 to 6.5 m depending on the exposure) 95%	25.1 km^2 (1% of the total CT area)	5.2 billion R (794 million US$)
Scenario 2 (+ 4.5 m) 85%	60.9 km^2 (2% of the total CT area)	23.7 billion R (30.3 billion US$)
Scenario 3 (+6.5 m) 20%	95 km^2 (4% of the total CT area)	54.8 billion R

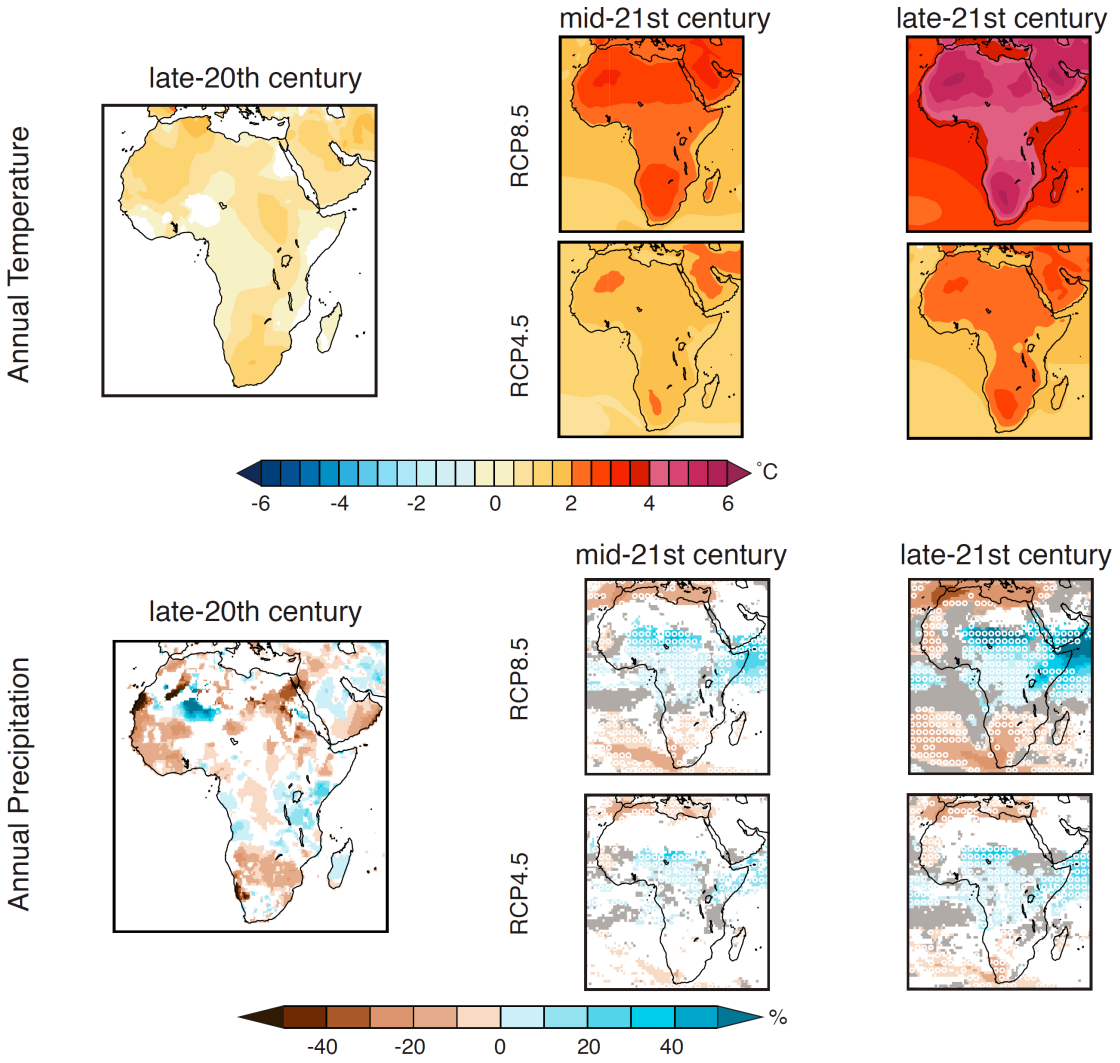
Note: The economic impacts are determined based on the value of properties, losses of touristic revenues and the cost of infrastructure replacement. The total geographical gross product for Cape Town in 2008 was 165 billion of Rands.

Table 22-3. Projected changes in agro-climatic suitability for perennial crops in Africa under an A2 scenario.

Crop	Suitability change	Country	Source
Coffee	Increased suitability at high latitudes; decreased suitability at low latitudes	Kenya	Läderach et al., 2010
Tea	Decreased suitability	Uganda	Eitzinger et al., 2011a,b
	Increased suitability at high latitudes; decreased suitability at low latitudes	Kenya	
Cocoa	Constant or increased suitability at high latitudes; decreased suitability at low latitudes	Ghana, Côte d'Ivoire	Läderach et al., 2011b
Cashew	Increased suitability	Ghana, Côte d'Ivoire	Läderach et al., 2011a
Cotton	Decreased suitability	Ghana, Côte d'Ivoire	Läderach et al., 2011c

Table 22-4: Cross-cutting approaches for equity and social justice in adaptation.

Equitable adaptation approach	Key issues to address for adaptation	Factors that could cause maladaptation	Opportunities	Lessons learned
Gender mainstreamed adaptation in Africa	Lack of empowerment and participation in decision-making (Patt et al, undated) Climate impacts increase women's household roles and may result in girls being kept out of school to assist (Raworth, 2008; UNDP, 2011; Romero Gonzalez et al, 2011) Male adaptation strategies e.g. migration may increase women's vulnerability (Djoudi and Brockhaus, 2011)	Employment opportunities are frequently not sufficiently extended to women in adaptation response frameworks (Madzwamuse, 2010). Failure to incorporate power relations in adaptation responses (Romero Gonzalez et al, 2011; Djoudi and Brockhaus, 2011)	Women's aptitude for long-term thinking, trusting and integrating scientific knowledge, and taking decisions in uncertain conditions (Patt et al, undated) Potential long-term positive changes in women's empowerments, roles and social and economic status (Djoudi and Brockhaus, 2011) Women opportunistically using development projects to adapt to climate change (Nielson, 2010)	Security of tenure over land and resource access is critical for enabling enhanced adaptive capacity of women (African Development Forum, 2010; add refs) Research on understanding different adaptive strategies of benefit for women and men is needed
Child-centered approaches to adaptation	Children and youth represent over 60% of Africa's population, yet their issues are largely absent from adaptation policy (African Development Forum, 2010) Children's differential vulnerability to projected climate impacts is high, particularly to hunger, malnutrition and disasters (Unicef, 2007)	Limits to children's agency related to power imbalances between children and adults, and different cultural contexts (Seballos et al, 2011)	Using approaches that stress agency and empowerment, and 'innovative energies' of youth; build on targeted adaptation initiatives, such as child-centred disaster risk reduction and adaptation (African Development Forum, 2010; Seballos et al., 2011)	Children and youth can play a positive role as change agents for climate adaptation, within an appropriate enabling environment Child-sensitive programmes and policies can reduce risks children face from disasters (Seballos et al, 2011) Funding for climate resilience programmes is necessary to protect children's basic rights (Unicef, 2010; Unicef, 2011)
Human rights-based approaches	Common critical rights issues for local communities are land/resource rights, gender equality, and political voice and fair adjudication of grievances for the poor and excluded (Castro et al, 2012).	Lack of recognition and promotion of their human rights blocks indigenous peoples' coping and adaptation capacities (UNPFII, 2008).	Using the HRBA lens to understand, for example, climate-related disaster risk, necessitates risk analysis to probe the root causes of the vulnerabilities that heighten disaster risk of certain groups, allowing for a structural and sustainable response (Urquhart, 2013)	Applying HRBA presents a framework for addressing conflicting rights and interests, necessary for equitable adaptation responses (Nilsson and Schnell, 2010)



Maps: Change in annual temperature and precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

Figure 22-1: Observed and simulated variations in past and projected future annual average precipitation and temperature.

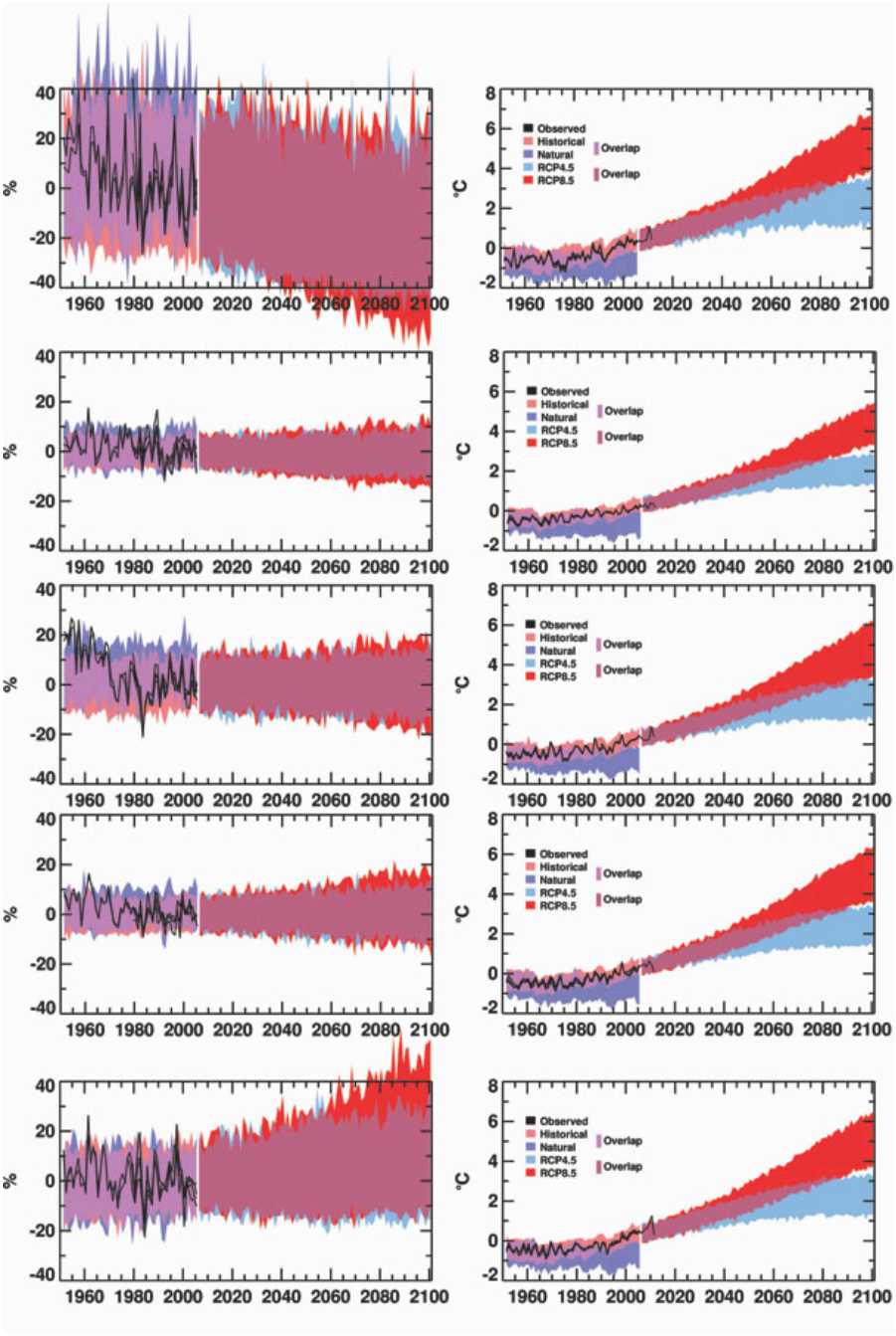


Figure 22-2: Observed and simulated variations in past and projected future annual average precipitation and temperature over five African regions (Arab Maghreb Union- AMU, Common Market for Eastern and Southern Africa – COMSEA, Southern African Development Community – SADC, Economic Community of West African States – ECOWAS, Economic Community of Central African States – ECCAS). Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3. The regions are described in 22.1.2, but COMESA-north covers COMESA north and inclusive of Rwanda, Uganda, and Kenya. Precipitation is included for land territories only, while temperature is included for both land and exclusive economic zone territories.

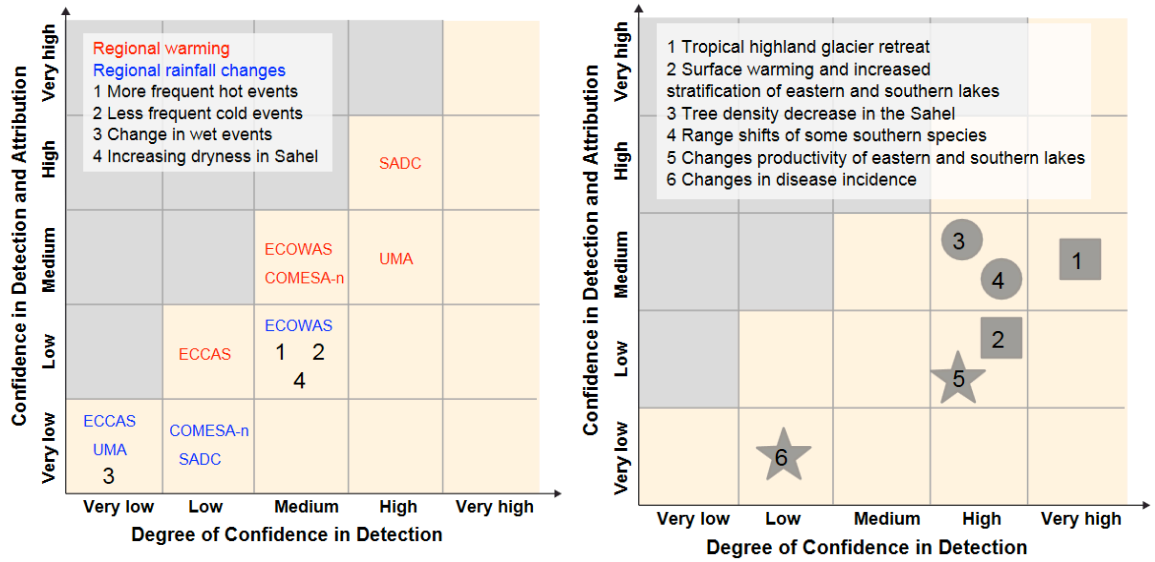


Figure 22-3: Summary of detection and attribution assessments of the relation of observed climate change over Africa with anthropogenic emissions (left) and of the relation of observed changes in natural and human systems with observed regional climate changes (right). All detection assessments are against a no-change reference and all attribution assessments for a major role of anthropogenic emissions (left) or observed regional climate change (right), except for "change in disease incidence" for which the detection assessment is relative to what would have been expected based on changes in livelihoods and health care and for which the attribution assessment is for a minor role of climate change in disease incidence. COMESA-n covers the half of COMESA north of and including Rwanda, Uganda, and Kenya. Discussion of these assessments are in 22.2, 22.3, 22.5.1, WGI AR5 Chapter 10, SREX 3.3, SREX 3.5, and 18.5.1. The detection and attribution assessments follow the specifications described in 18.2.

Figure 22-4: Number of undernourished people in Africa between 1994/1996 and 2010/2012
Source: www.fao.org/fileadmin/templates/ess/foodsecurity/Food_Security_Indicators.Xlsx.

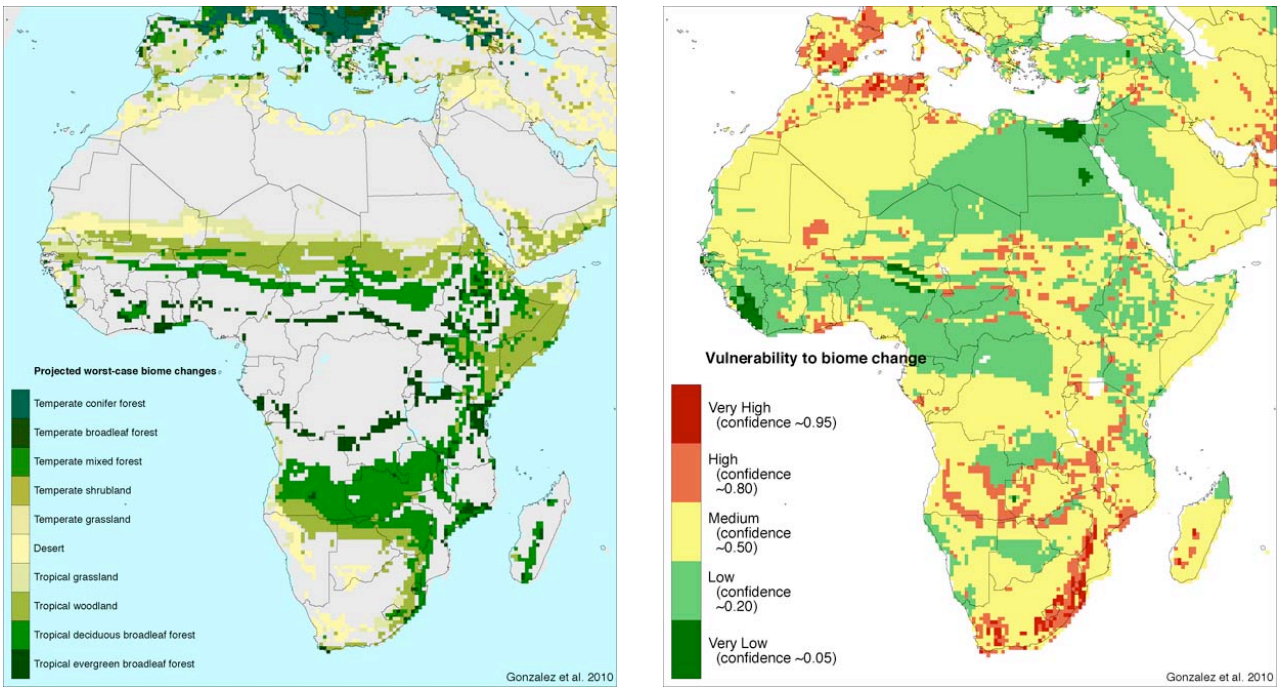


Figure 22-5: (a) Potential changes in vegetation between the periods 1961-1990 and 2071-2100, where any of nine combinations of three GCMs (CSIRO Mk3, HadCM3, MIROC 3.2 medres) and three emissions scenarios (B1, A1B, A2) project change. This is the worst case in comparison to the case of complete agreement of the nine combinations. (b) Vulnerability of ecosystems to biome shifts based on historical climate (1901-2002) and projected vegetation (2071-2100), where all nine GCM-emissions scenario combinations agree on the projected biome change. Source: Gonzalez *et al.* (2010).]

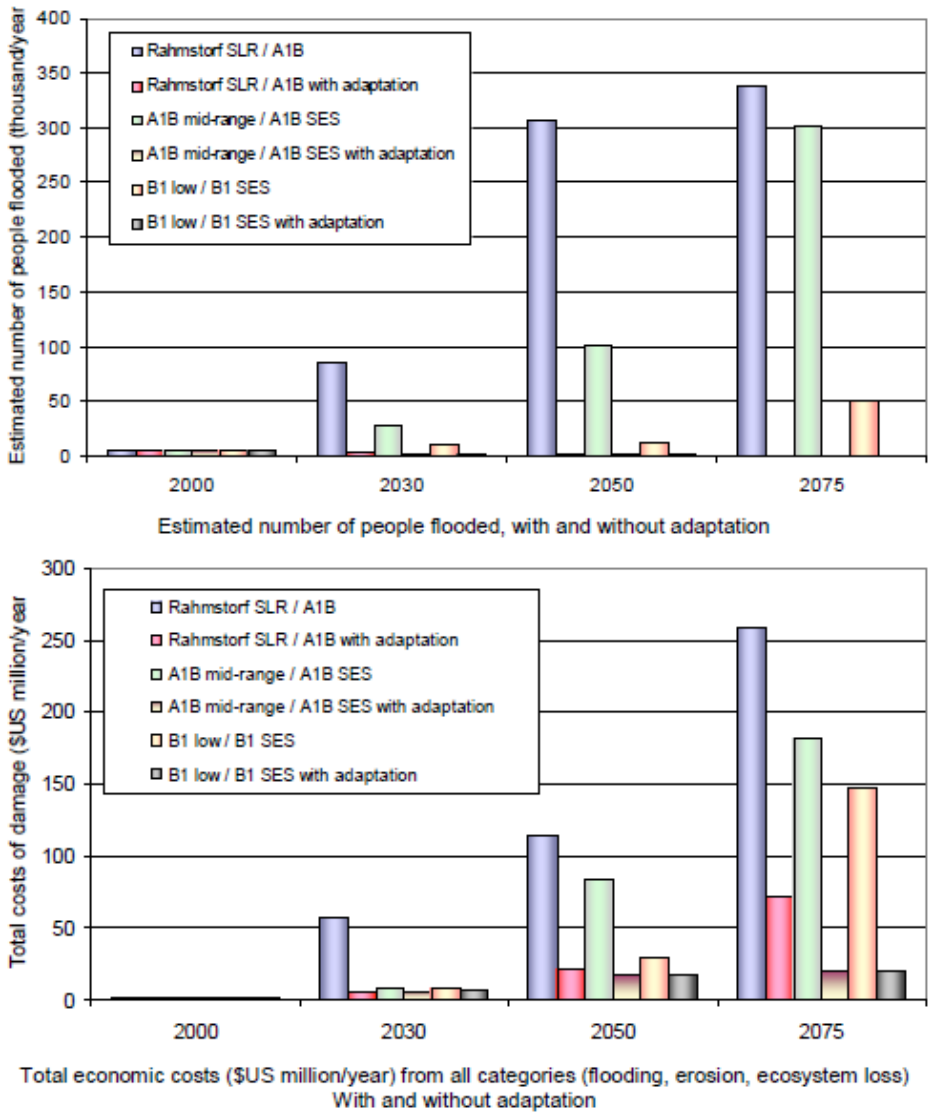


Figure 22-6: Population and economic losses in case of climate change for the whole Kenya coastal zone. Source: (SEI, 2009).

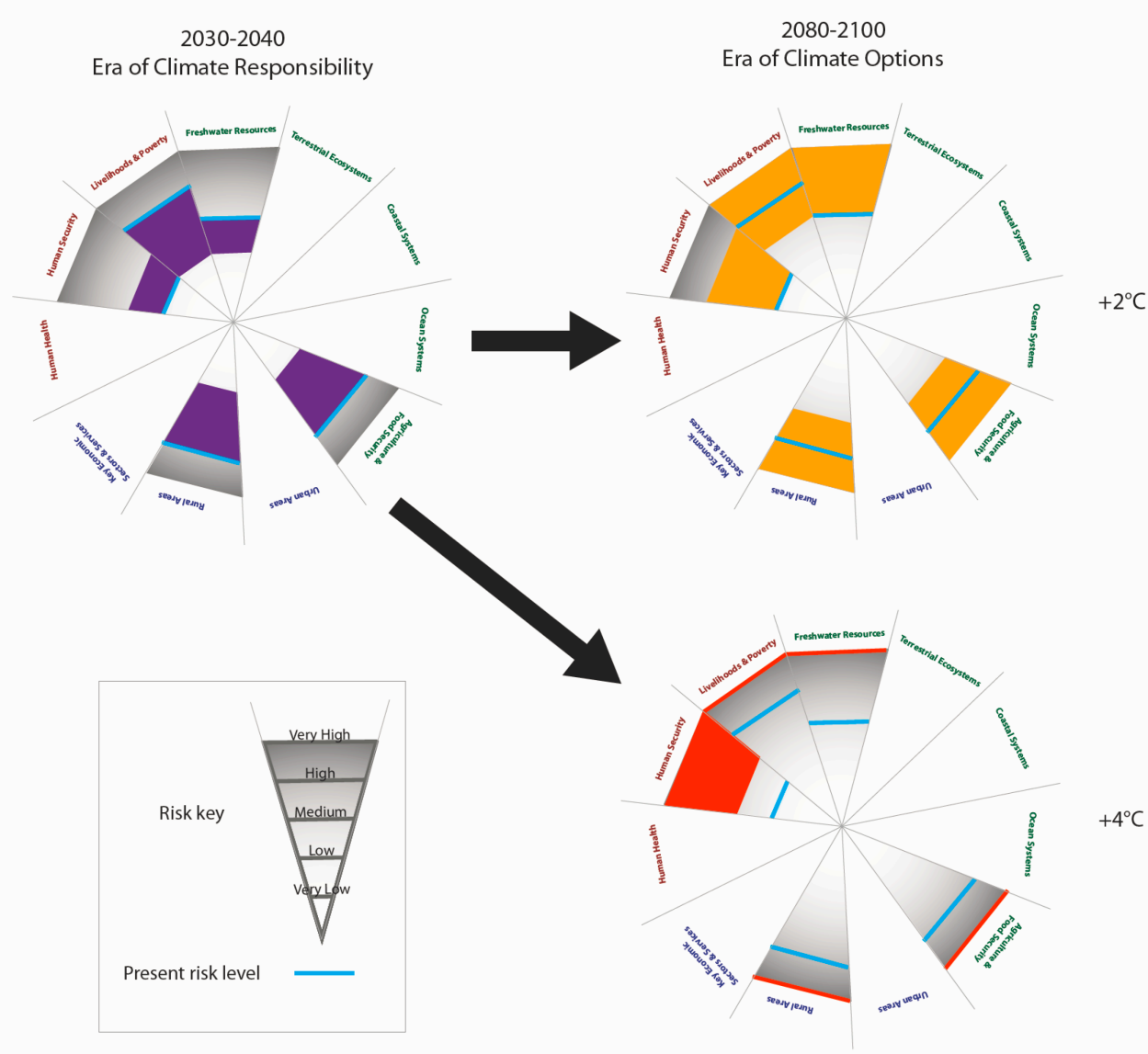


Figure 22-7: Risks for the present (blue line), for the near-term (2°C for 2030-2040) and for the end of the century for 2 temperatures (2°C and 4°C for 2080-2100). Risks are depicted for low adaptation and high adaptation.

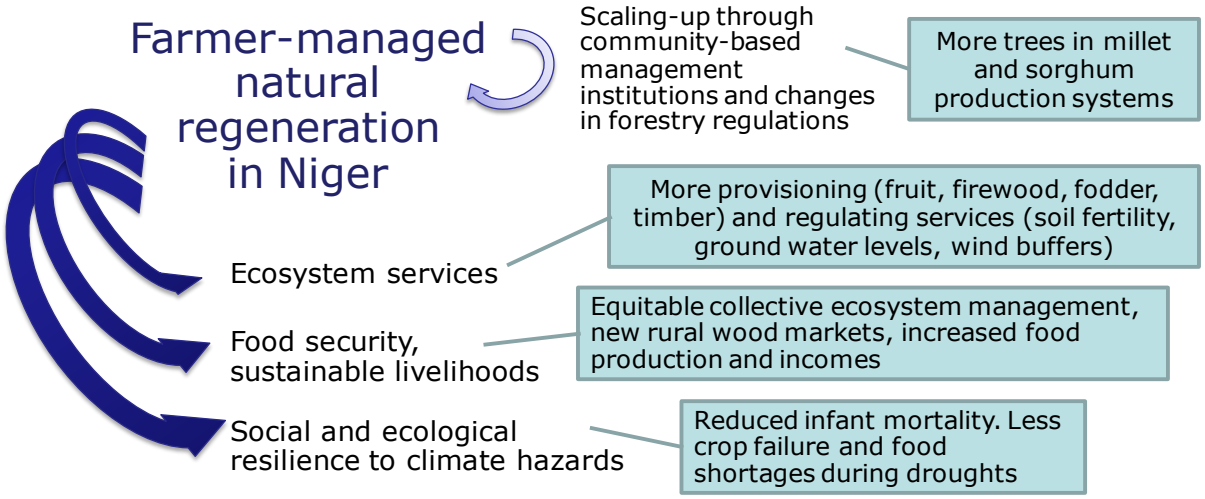


Figure 22-8: Ecosystem-based adaptation - Farmer Managed Natural Regeneration (FMNR): Benefits of ecosystem management for livelihoods and resilience (Garrity et al. 2010; Haglund et al. 2011; Reij et al. 2009; Sendzimir et al. 2011).

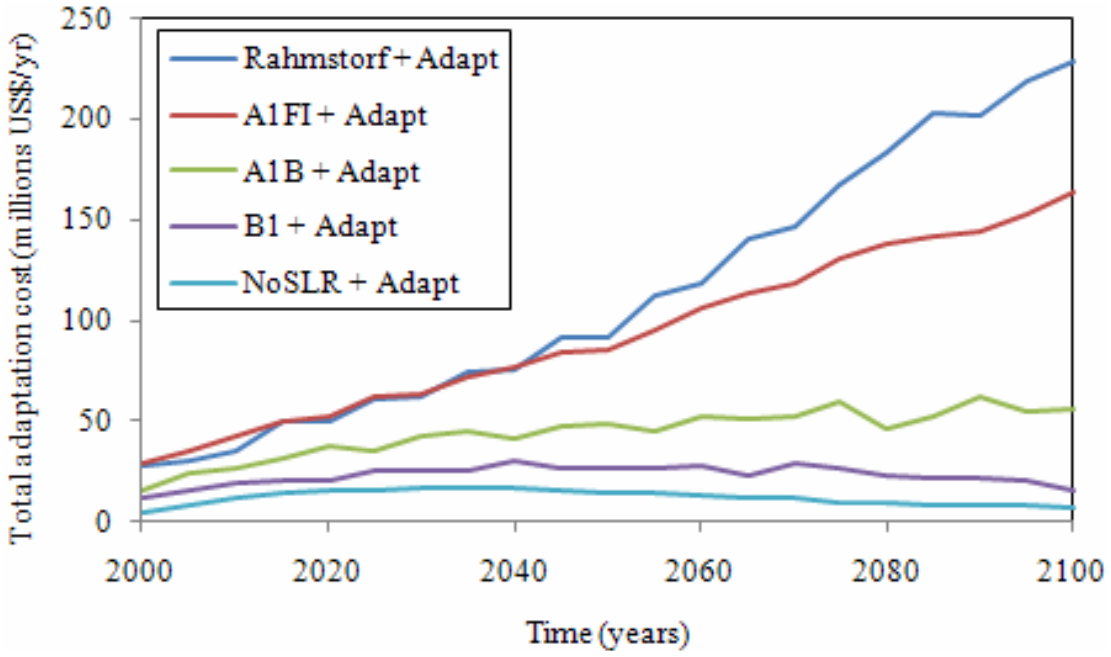


Figure 22-9: Total costs of adaptation per year from 2000 to 2100 for Tanzania (including beach nourishment and sea and river dikes) Source: Kebede et al., 2010.]

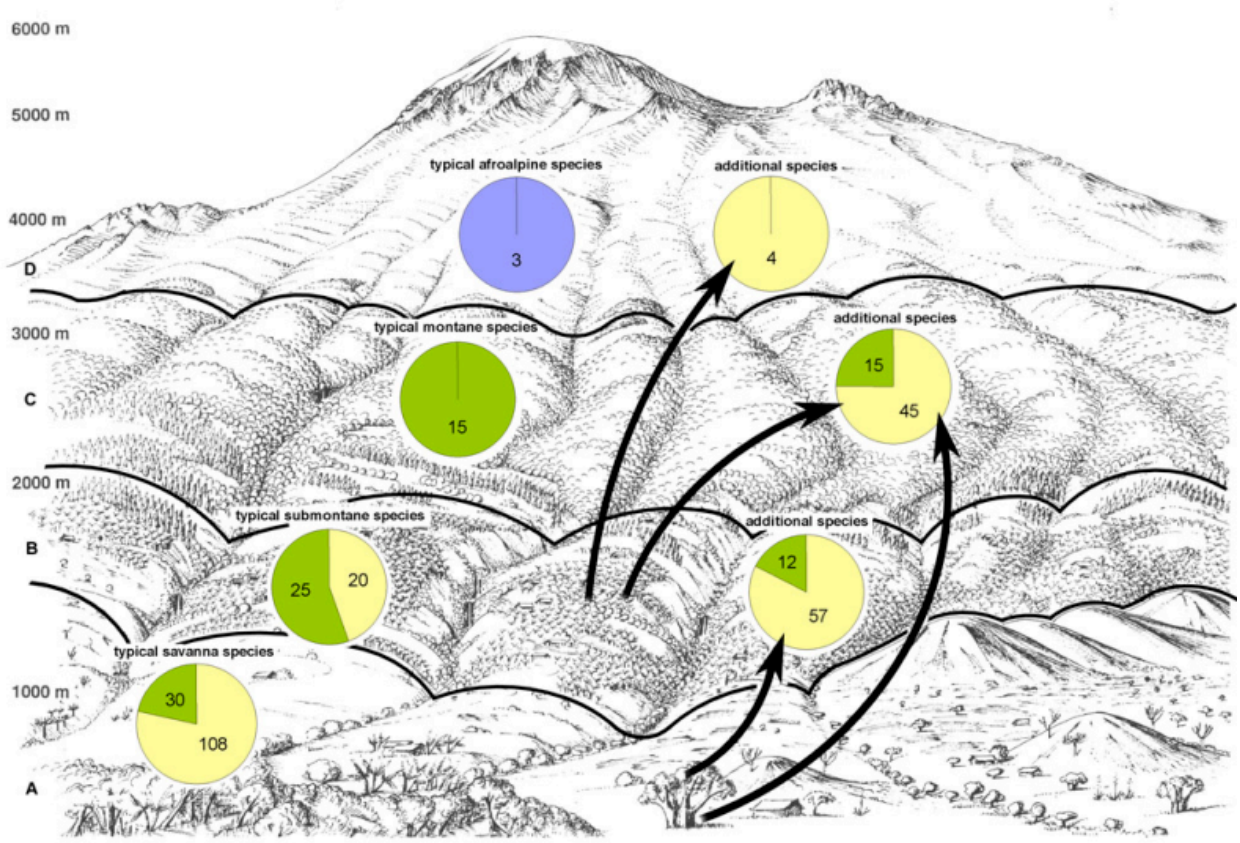


Figure 22-10: Upward movement of grasshoppers and bushcrickets at Kilimanjaro. Left circles giving numbers of species which are typical for this zone; right circles giving numbers of species that are additionally found to the typical species of the respective zone, arrows indicating area from which they migrated upwards. Yellow: openland forms, green: forest forms; blue: afroalpine forms. A: colline lowland savanna area, B: submontane and lower montane zone, C: montane zone, D: (sub) alpine zone. Source: Hemp and Hemp, 2008.

Chapter 23. Europe

Coordinating Lead Authors
Sari Kovats (UK), Riccardo Valentini (Italy)

Lead Authors
Laurens M Bouwer (Netherlands), Elena Georgopoulou (Greece), Daniela Jacob (Germany), Eric Martin (France), Mark Rounsevell (UK), Jean-Francois Soussana (France)

Contributing Authors
Martin Beniston (Switzerland), Maria Vincenza Chiriacò (Italy), Philippe Cury (France), Michael Davies (United Kingdom), Paula Harrison (United Kingdom), Olaf Jonkeren (Italy), Mark Koetse (Netherlands), Markus Lindner (Finland), Andreas Matzarakis (Germany), Reinhard Mechler (Germany), Annette Menzel (Germany), Marc Metzger (UK), Luca Montanarella (Italy), Antonio Navarra (Italy), Juliane Peterson (Germany), Martin Price (UK), Boris Revich (Russia), Piet Rietveld (Netherlands), Cristina Sabbioni (Italy), Yannis Sarafidis (Greece), Philipp Schmidt-Thomé (Finland), Vegard Skirbekk (Austria), Donatella Spano (Italy), Jan E Vermaat (Netherlands), Meriwether Wilson (UK), Thomasz Zylicz (Poland)

Review Editors
Lucka Kajfez Bogataj (Slovenia), Roman Corobov (Moldova), Ramón Vallejo (Spain)

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References

Executive Summary

Observed climate trends and future projections confirm the main conclusions of AR4 regarding current and future climate change in Europe [23.2]: climate models project significant changes in temperature [high confidence] and rainfall [high confidence] in Europe [23.2.1] with increases in temperature projected throughout Europe and

increasing precipitation in the North and decreasing precipitation in the South [23.2.2.2]. There will be a marked increase in the frequency and intensity of heat waves [high confidence], meteorological droughts [medium confidence] and heavy precipitation events [high confidence] with variations across Europe [23.2.2.3]; small or no change in wind speed extremes [low confidence] except increases in winter peak wind speed over Northern Europe [medium confidence] [23.2.2.3].

Climate change in Europe has already affected multiple sectors: distribution and composition of animals and plant species [high confidence] [Table 23.6, Table 23.4, 23.6.4]; crop yields in relation to European sub-regions [medium/high confidence] [23.4.1]; health, particularly in Southern Europe [medium confidence] [23.5.1]; forests due to increase of wildfires in Southern Europe [high confidence] and from storms [low confidence] [23.4.4] and European cultural heritage[low confidence] [23.5.4] [Table 23.6]. The observed impacts of extreme weather events indicates the current vulnerability of Europe across multiple sectors [Table 23.3]. Climate change will increase the frequency and intensity of heat waves, particularly in Southern Europe [high confidence] [23.2.2] with adverse implications for health, agriculture, energy production, transport, tourism, labour productivity, and built environment [Table 23.4].

Climate change in Europe will affect multiple sectors [Table 23-4]. All of the ecosystem services (Provisioning, Regulating and Cultural services) will be degraded by climate change at least in one or more European sub-regions. The most affected ecosystem services are: Cultural, Regulating and Provisioning services [Table 23.2].

Climate change will affect economic activity in southern Europe more than other sub-regions [medium confidence] [Table 23.4, 23.9.1], and increase future intra-regional disparity [low confidence] [23.9]. The Mediterranean (part of Southern region) is particularly vulnerable to climate change [high confidence] as multiple sectors will be adversely affected (tourism, agriculture, forestry, infrastructure, energy, population health) [high confidence] [23.9] [Box 23-3]. Compared to AR4, there is more evidence of risks in northern Europe in several sectors. Shifts in agriculture production across sub-regions will occur [medium confidence]. Loss of ecosystem services is projected in Alpine regions [high confidence] [23.10].

Synthesis of evidence across sectors and subregions confirm that there are limits to adaptation from social, economic and technological factors [23.5]. Adaptation is further impeded because climate change affects multiple sectors [23.10]. The majority of assessments are based on climate projections driven by lower emissions than the current trajectory. Limited evidence exists potential impacts in Europe under high rates of warming (>3-4 degrees per century) [23.10], with the exception of some studies of crop yields.

Sectoral impacts

Direct economic river flood damages in Europe have increased over recent decades [high confidence] but this increase is due to development in flood zones and not due to observed climate change [23.3.1.2, SREX 4.5]. Some areas in Europe show changes in river flood occurrence related to observed changes in extreme river discharge [medium confidence] [23.2.3]. Climate change is likely to further increase coastal and river flood risk in Europe and, if unabated, will substantially increase flood damages (monetary losses and people affected) [23.3.1, 23.5.1]. Adaptation can prevent most of the projected damages [high confidence – based on medium evidence, high agreement] [23.3.1; 23.7.1; 23.8.3]. Climate change will increase the problems associated with overheating in domestic housing [medium confidence] [section 23.3.2].

No significant impacts are projected before 2050 in winter or summer tourism except for ski tourism in low altitude and mid altitude sites and under limited adaptation [medium confidence] [23.3.6]. After 2050, tourism activity will decrease in southern Europe [low confidence] and increase in northern/continental Europe [medium confidence]. Artificial snowmaking will prolong the activity of some ski resorts [medium confidence] [23.3.6].

Climate change will affect the impacts of hot and cold weather extremes on transport leading to economic damage and/or adaptation costs, as well as some benefits (e.g. reduction of maintenance costs) during winter [medium confidence] [23.3.3]. Climate change will reduce severe accidents in road transport [medium confidence] and adversely affect inland water transport particularly the Rhine in summer after 2050 [medium confidence]. Damages

to rail infrastructure from high temperatures will increase [medium confidence]. Adaptation through maintenance and operational measures can reduce adverse impacts to some extent.

Climate change will decrease hydropower production from reductions in rainfall in all sub-regions except Scandinavia [high confidence] [23.3.4]. Climate change will have no impact on wind energy production before 2050 [medium confidence] and only a small impact after 2050 [low confidence]. Climate change will inhibit thermal power production during summer [medium confidence] [23.3.4]. Plant modifications and operational changes can reduce adverse impacts. Climate warming will decrease space heating demand [high confidence] and increase cooling demand [high confidence]; the income growth drives largest part of this increase during 2000-2050 period (especially in eastern regions) [medium confidence] [23.3.4]. Energy efficient buildings and cooling systems as well as demand-side management will reduce future energy demands [23.3.4].

Heat-related deaths and injuries will increase, particularly in Southern Europe [medium confidence] [23.5.1]. Climate change will change the distribution and seasonal pattern of some human infections, including those transmitted by arthropods [medium confidence]. The introduction of new infectious diseases due to climate change is unlikely [medium confidence] [23.5.1]. Climate change and sea level rise will damage European cultural heritage, including buildings, local industries, landscapes, and iconic places such as Venice [medium confidence] and some cultural landscapes will be lost forever [low/medium confidence] [23.5.4] [Table 23.5].

Climate change will alter the productivity of bioenergy crops in Europe by shifting their distribution northward [high confidence] [23.4.5]. Elevated atmospheric CO_2 can improve drought tolerance of bioenergy crop species due to improved plant water use, maintaining high yields in future climate scenarios [medium confidence] [23.4.5].

Yields of some arable crop species like wheat have been negatively affected by observed warming in some European countries since 1980s [medium confidence, limited evidence][23.4.1] Compared to AR4, new evidence regarding future yields in Northern Europe, is less consistent regarding the magnitude and sign of change. Climate change will increase yields in Northern Europe [medium confidence] but decrease cereal yields in Southern Europe [high confidence] [23.4.1]. In Northern Europe, climate change will increase the seasonal activity of pests and plant diseases [high confidence] [23.4.1]. Climate change will adversely affect dairy production in Southern Europe because of heat stress in lactating cows [medium confidence] [23.4.2]. Climate warming has caused the spread of blue tongue disease in ruminants in Europe [high confidence] [234.2] and northward expansion of tick vectors [medium confidence] [23.4.2, 23.5.1].

Climate change will change the geographic distribution of wine grape varieties [high confidence] and this will reduce the economic value of wine products and the livelihoods of local wine communities in Southern and Continental Europe [medium/low confidence] [23.4.1, 23.3.5, 23.5.4]. Some adaptation is possible through technologies and good practice [Box 23-1].

Climate change will increase irrigation needs [high confidence] but future irrigation will be constrained by reduced runoff, demand from other sectors, and by economic costs [23.4.1, 23.4.3]. By 2050s, irrigation will not be sufficient to prevent damage from heat waves to crops [medium confidence]. System costs will increase under all climate scenarios [high confidence] [23.4.3]. Integrated management of water is needed to address future competing demands between agriculture, conservation and human settlements [23.7.2].

Observed warming has shifted sea fish species ranges to higher latitudes [high confidence] and reduced body size in species [low confidence] [23.4.6]. Climate change will not decrease net fisheries economic turnover in some parts of Europe (e.g. Bay of Biscay) [low confidence] due to introduction of new (high temperature tolerant) species. Climate change will not entail relocation of fishing fleets [high confidence] [23.4.6]. Observed higher water temperatures have adversely affected both wild and farmed freshwater salmon production [high confidence] [23.4.6]. High temperatures will increase frequency of harmful cyanobacterial blooms [medium confidence] [23.4.6].

Climate warming has adversely affected trends in ground level tropospheric ozone [low confidence] [23.6.1.]. Climate change will increase the frequency of tropospheric ozone events (exceedences) in the future [low

confidence] even assuming future emissions reductions [23.6.1]. Climate change will decrease surface water quality due to higher temperatures [medium confidence] [23.6.3]. There is little evidence regarding the effect of climate change on soil erosion, salinisation or soil fertility [23.6.2].

Observed climate warming has increased forest productivity in northern Europe [medium confidence] [23.4.4] and fire incidence in southern Europe [high confidence] [23.4.4]. Climate change will increase damage from pests and diseases in all sub-regions [high confidence] [23.4.4] and damage from wildfires in Southern Europe [high confidence] and from storms [low confidence] [23.4.4]. Climate change will cause ecological and socio-economic damages from shifts in forest tree species range, with a general trend of a south-west to north-east [medium confidence], and in pest species distributions [low confidence] [23.4.4]. Short-term and long-term strategies in forest management may be an adequate measure to enhance ecosystem resistance and resilience [medium confidence] [23.4.4].

Observed climate change is affecting a wide range of flora and fauna, including plant pests and diseases [medium confidence] [23.4.1, 23.4.4] and the vectors of animal diseases [medium confidence] [23.4.3]. Climate change will cause changes in habitats and species, with local extinction [high confidence] and continental scale shift in Europe [medium/low confidence] [23.6.4]. The habitat of alpine plants will be significantly reduced [high confidence] [23.6.4]. Phenological mismatch will constrain both terrestrial and marine ecosystem functioning under climate change [high confidence] [23.6.4, 23.6.5], with a reduction in some ecosystem services [low confidence] [23.6.4]. The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe will increase with climate change [medium confidence] [23.6.4]. Climate change will entail the loss or movement of coastal wetlands [high confidence] [23.6.5]. Conservation policies and selection of protected areas have not considered so far impact of climate changes. Biodiversity is affected in unprotected areas more than in protected areas but Natura 2000 areas retain climate suitability for species no better and sometimes less effectively than unprotected areas [low confidence] [23.6.4].

Cross-sectoral adaptation

The capacity to adapt in Europe will be higher than for other world regions, but there are important differences in impacts and the capacity to respond within the European sub-regions. In Europe, adaptation policy has been developed at international (EU), national and local government level [23.7] but so far evidence relates to studies of the prioritisation of options, and there is limited systematic information on current implementation (or effectiveness) [Box 23-2]. Some adaptation planning has been integrated into coastal and water management, as well as disaster risk management [23.7.1; 23.7.2; 23.7.3]. There is little evidence of adaptation planning in rural development or land-use planning [23.7.4; 23.7.5]. Economic estimates for adaptation requirements in Europe are available and increasingly from detailed bottom-up sector-specific studies for coastal defences, energy production, energy use, and agriculture [23.7.6]. The costs of adapting dwellings or upgrading coast defence will increase under all scenarios [high confidence] [23.3.2].

There are opportunities for policies that improve adaptive capacity and also help meet mitigation targets [23.8]. Some agricultural practices can potentially mitigate GHG emissions and at the same time adapt crops to increase resilience to temperature and rainfall variability [23.8.2]. Climate policy in transport and energy sectors to reduce emissions can improve population health [23.8.3] [high confidence]. However there are also potential for unintended consequences of mitigation policies in the built environment (especially housing) and energy sectors [23.8.1].

23.1. Introduction

This chapter reviews the scientific evidence published since AR4 on observed and projected impacts of anthropogenic climate change in Europe and adaptation responses. The geographical scope of this chapter is the same as in AR4 with the inclusion of Turkey. Thus, the European region includes all countries from Iceland in the west to Russia (west of the Urals) and the Caspian Sea in the east, and from the northern shores of the Mediterranean and Black Seas and the Caucasus in the south to the Arctic Ocean in the north. Impacts above the Arctic Circle are addressed in the Polar Regions Chapter 28 and impacts in the Baltic and Mediterranean Seas are

addressed in the Open Oceans Chapter 30. Impacts in Malta and other island states in Europe are discussed in the Small Island Chapter 29.

The European region has been divided into 5 sub-regions (see Figure 23-1): Atlantic, Alpine, Southern Northern, and Continental. The sub-regions are derived from climate zones developed by Metzger *et al.* (2005) and therefore represent geographical and ecological zones rather than political boundaries. The scientific evidence has been evaluated according to compare impacts across (rather than within) sub-regions, however, this is not always possible, depending on the scientific information available.

[INSERT FIGURE 23-1 HERE
Figure 23-1: Sub-regional classification of the IPCC Europe region. Based on Metzger et al., 2005.]

23.1.1. Scope and Route Map of Chapter

The chapter is structured around key policy areas. Sections 23.3 to 23.6 summarise the latest scientific evidence on climate sensitivity, observed impacts and attribution, projected impacts and adaptation options, with respect to four main categories of impacts:

- production systems and physical infrastructure;
- agriculture, fisheries, forestry and bioenergy production;
- health and social welfare and;
- protection of environmental quality and biological conservation.

The benefit of assessing evidence in a regional chapter is that integrated impacts across sectors can be described, as well as cross-sectoral decision making required to address many climate change issues.

The chapter also evaluates the scientific evidence in relation to the five sub-regions discussed above. The majority of the research in the Europe region is for impacts in countries in the European Union due to targeted research funding through the European Commission which means that countries in eastern Europe and Russia are less well represented in this chapter. Further, regional assessments may be reported for the EU15, EU27 or EEA (32) group of countries [see supplemental information for list of countries in each group].

This chapter includes several sections that were not in AR4. Because many adaptation and mitigation policies are now in place in Europe, the evidence for potential co-benefits and unintended consequences of such strategies is reviewed (Section 23.8). The implications of climate change for the distribution of economic activity within European region is discussed in Section 23.9. The final section synthesise the key findings with respect to: observed impacts of climate change, key vulnerabilities and identifies research gaps.

23.1.2. Policy Frameworks

Since AR4, there have been significant changes in Europe in responses to climate change. More countries now have adaptation and mitigation policies in place. An important force for climate policy development in the region is the European Union (EU). EU Member States have mitigation targets, as well as the overall EU target, with both sectoral and regional aspects to the commitments.

Adaptation policies and practices have been developed at the international, national and local levels although research on implementation of such policies is limited. Due to the vast range of policies, strategies and measures it is not possible to describe them extensively here. However, adaptation in related to cross-sectoral decision-making is discussed in section 23.7 (see also Box 23-2 on national adaptation policies). The EU Adaptation Platform catalogues adaptation actions reported by Member States. The EU adaptation strategy is due in March 2013. See Chapter 15 for a more extensive discussion of institutions and governance in relation to adaptation planning and implementation in Europe.

23.1.3. Conclusions from Previous Assessments

AR4 documented a wide range of impacts of observed climate change in Europe (AR4 WG2 Chapter 12). The SREX confirmed increases in warm days, warm nights and decreases in cold days and cold nights since 1950 (*high confidence*, SREX-3.3.1). Extreme precipitation increased in part of the continent, mainly in winter over western-central Europe and European Russia (*medium confidence*, SREX-3.3.2). Dryness has increased mainly in Southern Europe (*medium confidence*, SREX-3.3.2). Climate change was expected to magnify regional differences within Europe for natural resources (in particular for agriculture and forestry) because water stress was projected to increase over central and southern Europe (AR4-12.4.1, SREX-3.3.2, SREX-3.5.1). Many climate related hazard were projected to increase in frequency and intensity, but with significant variations within the region (AR4-12.4).

The AR4 identified that climate changes would pose challenges to many economic sectors and was expected to alter the distribution of economic activity within Europe (*high confidence*). Adaptation measures were evolving from reactive disaster response to more proactive risk management. A prominent example was the implementation of heat health warning systems following the 2003 heat wave event (AR4 WG2 12.6.1, SREX 9.2.1). National adaptation plans were developed and specific plans were incorporated in European and national policies (AR4 WG2 12.2.3, 12.5) but these were not integrated comprehensive, or evaluated (AR4 WG2 12.8).

23.2. Current and Future Trends

23.2.1 Non- Climate Trends

Countries in the European region are diverse with respect to both demographic and economic trends. Population health and welfare in all European countries has been improving, with reductions in adult and child mortality rates. However, inequalities both within and between countries in Europe persist (Marmot *et al.*, 2012). Population is generally increasing in the EU27 countries, primarily due to net immigration although population growth is slow (total and working age population) (Rees *et al.*, 2012). Some countries, including the Russian Federation, have had decreases in population since the 1990s. Migration pressure into Europe is increasing (Eurostat, 2011a) but within the EU27 movement between countries is encouraged as part of economic policy. The ageing of the population is a significant trend in Europe, as in all high income populations. This will have both economic and social implications, and many regions are likely to experience a decline in labour force (Rees *et al.*, 2012).

Since AR4, economic growth has slowed (or stalled) in several European countries. In some countries, this has been associated with a reduction in social protection measures and increased unemployment (Eurostat, 2011b). The longer term implications of the financial crisis in Europe are unclear, although it will probably lead to some modification of the economic outlook and may affect future social protection policies (with implications for adaptation).

Agriculture is the most dominant European land use and. Europe is one of the world's largest and most productive suppliers of food and fibre. Rapid changes to farming systems in the post-war decades allowed an unprecedented increase in agricultural productivity, but also had a number of negative impacts on the ecological properties of agricultural systems, such as carbon sequestration, nutrient cycling, soil structure and functioning, water purification, and pollination. Most scenario studies suggest that agricultural land areas will continue to decrease in the future as they have done over the past 50 years (see Busch (2006) for a discussion). Agriculture accounts for 22 % of total national freshwater abstraction in Europe and more than 80 % in some southern European countries (EEA, 2009). Limited water availability is already a significant problem in many parts of Europe and the situation is likely to deteriorate further in future decades. Economic restructuring in some eastern European countries has led to a decrease in water abstraction for irrigation, suggesting the potential for future increases in irrigated agriculture and water use efficiency (EEA, 2009). Water allocation between upstream and downstream countries is challenging in regions exposed to prolonged droughts such as the Euphrates-Tigris river basin, where Turkey plans to more than double water abstraction by 2023 (EEA, 2010a).

The forested areas of Europe account for approximately 35% of the land area (Eurostat, 2009). The majority of forests now grow faster than in the early 20th century due to advances in forest management practices, genetic improvement and in central Europe, the cessation of site-degrading practices such as litter collection for fuel. It is also very likely that increasing temperatures and CO_2 concentrations, nitrogen deposition, and the reduction of air pollution (SO_2) have had a positive effect on forest growth. Land use scenarios suggest that forested areas will expand in Europe in the future on land formerly used for agriculture (Rounsevell *et al.*, 2006).

Soil degradation is already intense in parts of the Mediterranean and central-eastern Europe and, together with prolonged drought periods and increased numbers of fires, is already contributing to an increased risk of desertification. Projected risks for future desertification are the highest in the same areas (EEA-JRC-WHO, 2008).

Europe has relatively moderate urban sprawl levels. Urbanisation is projected to increase all over Europe (Reginster and Rounsevell, 2006), but especially rapidly in Eastern Europe, with the magnitude of these increases depending on population growth, GDP growth and land use planning policy. Although changes in urban land use will be relatively small in area terms, urban development has major impacts locally on environmental quality. A recent past and likely future trend in Europe is peri-urbanisation in which residents move out of cities to locations with a rural character, but retain a functional link to cities by commuting for employment purposes (Reginster and Rounsevell, 2006) (Rounsevell and Reay, 2009). Other important environmental trends include improvements in outdoor air quality and declines in water quality (eutrophication) in some areas (ELME, 2007).

Several scenario studies have been completed for Europe covering socio-economic indicators (Mooij de and Tang, 2003), land use (Verburg *et al.*, 2010; Letourneau *et al.*, 2012)(Haines-Young *et al.*, 2012), land use and biodiversity (Spangenberg *et al.*, 2011), crop production (Hermans *et al.*, 2010), demographic change (Davoudi *et al.*, 2010), economics (Dammers, 2010) and European policy trends (Helming *et al.*, 2011)(Lennert and Robert, 2010). Many of these scenario studies also account for future climate change (see Rounsevell and Metzger (2010) for a review). Long term projections (to the end of the century) will be described under the new Shared Socio-economic Pathway scenarios (SSPs) (Kriegler *et al.*, 2010). Detailed country and regional scale socio-economic scenarios have also been produced for the Netherlands (WLO, 2006), the UK (UK National Ecosystem Assessment, 2011) and Scotland (Harrison *et al.*, 2012). Probabilistic representation of socio-economic futures have been developed for agriculture and land use change at the global scale level including Europe (Baumanns *et al.*, 2012; Hardacre *et al.*, 2012), although a lack of evidence remains about the use of probabilistic information (Bryson et al., 2010) or scenarios in general for policy making.

23.2.2. Observed and Projected Climate Change

23.2.2.1. Observed Climate Change

The average temperature in Europe has continued to increase, but with regionally and seasonally differences in the rate of warming. Since the 1980s, warming has been strongest over Scandinavia, especially in winter, whereas the Iberian Peninsula warmed mostly in summer (Haylock *et al.*, 2008). The decadal average temperature over land area for the period 2002-2011 is 1.3°C+/- 0.11°C above the 1850-1899 average (EEA, 2012), based on HadCRUT3 {{1535 Brohan, P. 2006}}, MLOST {{1537 Smith, T.M. 2008}} and GISSTemp {{1536 Hansen, J. 2010}}. Consistent with previous trends, the rate of warming has been greatest in high latitudes in Northern Europe (see also Polar Regions chapter 28). Observed regional climate change is also described in Chapter 21.

High-temperature extremes (hot days, tropical nights, and heat waves (Vautard R et al, 2013) have become more frequent, while low-temperature extremes (cold spells, frost days) have become less frequent in Europe (EEA, 2011). The recent cold winters in northern and western Europe reflect the high natural variability in the region (Peterson *et al.*, 2012), and do not contradict the general warming trend. In Eastern Europe, including the European part of Russia, summer 2010 was exceptionally hot, with an amplitude and spatial extent that exceeded the previous 2003 heat wave (Barriopedro *et al.*, 2011). These two heat waves revised the seasonal temperature records over approximately half of Europe.

Annual precipitation trends in the 20th century showed an increase in Northern Europe (10–40%) and a decrease in some parts of Southern Europe (up to 20 %) (EEA, 2008)(Del Rio *et al.*, 2011). At the continental scale, winter snow cover extent has a high variability and a non significant negative trend over the period 1967-2007 (Henderson and Leathers, 2010). For a more detailed assessment on regional observed changes in temperature and precipitation extremes (see Table 3-2 of SREX, (Berg *et al.*, 2013). Windspeeds have declined over Europe over the last decades (Vautard *et al.*, 2010) but there is a *low confidence* in this trend due to problematic anemometer data and climate variability (SREX, section 3.3).

Europe is marked by increasing mean sea level with regional variations, except in the Baltic sea where the relative sea level decreases due to vertical crustal motion (Haigh *et al.*, 2010; Menendez and WoodWorth, 2010; Albrecht *et al.*, 2011; EEA, 2012). Extreme sea levels increased due to mean sea level rise (*medium confidence*, SREX, section 3.5, (Haigh *et al.*, 2010; Menendez and WoodWorth, 2010). Few studies exist on waves (SREX, section 3.5, (Charles *et al.*, 2012) leading to a *low confidence* (based on poor evidence) of anthropogenic influence on the observed trends.

23.2.2.2. Projected Climate Changes

There is now more knowledge about the range of possible future climates in Europe, particularly sub-regional information from high resolution climate model output and downscaling (WGII Chapter 21). Within the recognized limitations of climate projections (see WGI Annex 1 (Atlas) and WGII Chapter 21), new research on inter-model comparisons have provided a more robust range of future climates with which to assess future impacts (WGI Chapter 9). Since AR4, climate impact assessments are able to use a range of temperature and rainfall changes rather a single average measure (ensemble mean). Europe is fortunate to have access to comprehensive and detailed sets of climate projections for decision making (SREX, section 3.2.1, (Mitchell *et al.*, 2004)(Fronzek *et al.*, 2012; Jacob *et al.*, 2013).

Even under a climate warming limited to 2°C compared to pre-industrial times, the climate of Europe is simulated to depart significantly in the next decades from today's climate (Jacob and Podzun, 2010)(Van der Linden and Mitchell). Climate models show significant agreement in warming (magnitude and rate) all over Europe, with strongest warming in Southern Europe in summer, and in Northern Europe in winter (Kjellström *et al.*, 2011)(Goodess *et al.*, 2009)(Schmidli *et al.*, 2007).

Precipitation signal is regionally and seasonally very different. Trends are less clear, but agreement in precipitation increase in Northern Europe and decrease in Southern Europe, the zone in between has less clear sign of change (*medium confidence*) (Kjellström *et al.*, 2011). Changes in the annual cycle indicate a decrease in precipitation in the summer months up to Southern Sweden, an increase in winter precipitation with more rain than snow and a decrease of long term mean snow pack (although snow-rich winters will remain) (Räisänen and Eklund, 2011). There is lack of information about past and future changes in hail occurrence. Changes in future circulation patterns are inconsistent, except in Northern Europe (Beck *et al.*, 2007)(Kjellström *et al.*, 2011)(Pryor and Barthelmie, 2010)(Pryor and Schoof, 2010)(Rockel and Woth, 2007)(Ulbrich *et al.*, 2009). Mean wind speed trends are rather uncertain due to shortcomings in wind simulations in GCMs (SREX and (McInnes *et al.*, 2011)).

Recent results highlight that regional coupled simulations over the Mediterranean region provide a better characterization of impact parameters, such as snow cover and aridity index. These simulations have detected changes in key impact indicators, such as snow or river discharge, which were not revealed by CMIP3 global simulations (Dell'Aquila *et al.*, 2012).

For the period 2081-2100 (compred to 1986-2005) the projected global sea level rise is in the range 0.29-0.55 for RCP2.6, 0.36-0.63 for RCP4.5, 0.37-0.64 for RCP6.0 and 0.48-0.82 for RCP8.5 (*medium confidence*, WG1, section 13.7.2). However, at the regional scale, changes can differ from the mean changes (Slangen *et al.*, 2012). There is a *low confidenc*e on projected regional changes (WG1, 13.7). Some high-end (low probability/high impact) estimates of extreme mean sea-level rise projections have been made for The Netherlands (Katsman *et al.*, 2011), indicating

that the mean sea-level could rise globally between 0.55 and 1.15 m, and locally (the Netherlands) by 0.40 to 1.05 m.

23.2.2.3. Projected Changes in Climate Extremes

There will be a marked increase in many types of extremes in Europe, in particular, in heat waves, droughts and heavy precipitation events (WGII Chapter 21, Lenderink and Van Meijgaard, 2008). Table 23-1 describes projected changes of selected climate parameters and climate indices for the period 2071-2100 with respect to 1971-2000, spatially averaged for the five Europe sub-regions.

[INSERT TABLE 23-1 HERE
Table 23-1: Projected Changes of Selected Climate Parameters and Indices[1] for the Period 2071-2100 with Respect to 1971-2000 Spatially Averaged for Europe Subregions. A) A1B scenario. Numbers are based on 9 (indicated with*) and 20 (indicated with **) regional model simulations taken from EU-ENSEMBLES project for the SRES A1B emission scenario. The likely range defines the range of 66% of all projected changes around the ensemble median. B) RCP4.5 scenario. Numbers are based on 7 (indicated with *) and 8 (indicated with **) regional model simulations taken from EURO-CORDEX project for the RCP 4.5 emission scenario. The likely range defines the range of 66% of all projected changes around the ensemble median.]

A detailed assessment on extremes in the future climate is reported in WGII Chapter 21 and SREX. There is a general *high confidence* concerning changes in temperature extremes (toward increased number of warm days, warm nights and heat waves, SREX, Table 3-3). Figure 23-2 shows projected changes in the mean number of heat waves in an extended summer season for the period 2071-2100 compared to 1971-2000 for SRES A1B and RCP4.5 with large differences depending on the emission scenario. The increase in likelihood of some individual events due to anthropogenic change has been quantified for the 2003 heat wave (Schär and Jendritzky, 2004), the warm winter of 2006/2007 and warm spring of 2007 (Beniston, 2009).

Changes in extreme precipitation depend on the region, with a *high confidence* of increased extreme precipitation in Northern Europe (all seasons) and Central Europe (except summer). Future projections are inconsistent in Southern Europe (all seasons) (SREX Table 3-3). Figure 23-3 shows projected seasonal changes of heavy precipitation events for the period 2071-2100 compared to 1971-2000 for SRES A1B and RCP4.5.

[INSERT FIGURE 23-2 HERE
Figure 23-2: Projected changes in the mean number of heat waves occurring in the months May to September for the period 2071-2100 compared to 1971-2000 (number per season) (Jacob et al, 2013). Heat waves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the daily maximum temperature of the May to September season of the control period (1971-2000) by at least 5°C. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test). For the eastern part of Turkey, unfortunately no regional climate model projections are available. A) Changes represent average over 9 regional model simulations (A1B) taken from the EU-ENSEMBLES project. B) Changes represent average over 8 regional model simulations (RCP4.5) taken from the EURO-CORDEX project.]

[INSERT FIGURE 23-3 HERE
Figure 23-3: Projected seasonal changes of heavy precipitation defined as the 95th percentile of daily precipitation (only days with precipitation > 1mm/day are considered) for the period 2071-2100 compared to 1971-2000 (%) (Jacob *et al.*, 2013). For the eastern parortunately no regional climate model projections are available. The figures are sorted as follows: left side (DJF, JJA) and right side (MAM, SON). Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test). A) Changes represent average over 20 regional model simulations (A1B) taken from the EU-ENSEMBLES project. B) Changes represent average over 7 regional model simulations (RCP4.5) taken from the EURO-CORDEX project.]

A number of studies based of GCMs and RCMs exhibit a small tendency toward increased extreme wind speed (A1B scenario, 2081-2100 relative to 1981-2000) in Northern Europe in winter in relation to changes in storm tracks (*medium confidence*, SREX, Figure 3-8 (Pinto *et al.*, 2007a; Pinto *et al.*, 2007b)(Rockel and Woth, 2007)(Donat *et al.*, 2010)(Pinto *et al.*, 2010)(Rauthe *et al.*, 2010)(Schwierz *et al.*, 2010)(Donat *et al.*, 2011)(McInnes *et al.*, 2011)(Haugen and Iversen, 2008). Over northern Europe small increase in winter peak wind speed is projected (WGII chapter 21, 21.4.1.1.3). In other parts of Europe, changes are inconsistent.

Extreme sea level events will increase (*high confidence*, WG1, 13.8, SREX 3.5.3), mainly dominated by the global mean sea level increase. Storm surge are expected to vary along the European coasts. Significant increases are projected in the eastern North Sea (increase of 6-8% of the 99th percentile of the storm surge residual, 2071-2100 compared to 1961-1990, based on the B2, A1B and A2 SRES scenarios (Debernard and Rÿed, 2008) and West of British Isles and Ireland (Debernard and Rÿed, 2008)(Wang *et al.*, 2008), except South of Ireland (Wang *et al.*, 2008). There is *medium agreement* for the South of North Sea and Dutch coast were trends vary from increasing (Debernard and Rÿed, 2008) to stable (Sterl *et al.*, 2009). There is a *low agreement* on the trends in storm surge in the Adriatic sea (Jordà *et al.*, 2012; Lionello *et al.*, 2012; Troccoli *et al.*, 2012)(Planton *et al.*, 2011).

23.2.3. Observed and Projected Trends in the Riverflow and Drought

Observed changes have occurred in river discharges in response to changing precipitation patterns and glacier mass balances (AR5 WG2 Chapter 3). Streamflows have decreased in the south and east of Europe and increased in northern Europe in small natural catchments (Stahl *et al.*, 2010)(Wilson *et al.*, 2010)(AR5 WG2 3.2.3). In general, there are large uncertainties in establishing flood trends in Europe (Kundzewicz *et al.*, 2013). In France, upward trends in low flow indices were observed over 1948-1988 and downward trends over 1968-2008 (Giuntoli *et al.*, 2013). Some studies show increases in extreme river discharge (peak flows) in parts of Germany (Petrow *et al.*, 2009)(Petrow *et al.*, 2007), the Meuse river basin (Tu *et al.*, 2005), parts of Central Europe (Villarini *et al.*, 2011), Russia (Semenov, 2011), and Northwestern France (Renard *et al.*, 2008); other studies show decreases in extreme discharges, for example, in the Czech Republic (Yiou *et al.*, 2006), or no change (Switzerland; (Schmocker-Fackel and Naef, 2010); Germany; (Bormann *et al.*, 2011). This pattern fits with analyses at the European level, because the high variability of extreme discharges is driven by atmospheric circulation variations (Bouwer *et al.*, 2008) (Kundzewicz *et al.*, 2010) [see also SREX report, AR5 WG2 Chapter 3]. One study suggests that river training partly masks increasing flood flows in the Rhine basin (Vorogushyn *et al.*, 2012). The attribution of the UK 2000 summer flood to anthropogenic forcing was proposed by (Pall *et al.*, 2011) although later study has shown a weaker effect (Kay *et al.*, 2011).

Future climate change is projected to affect future hydrology of river basins [SREX report, AR5 WG2 Chapter 4]. Europe wide analyses indicate increases in the occurrence of high river discharges (100-year return period) in Continental Europe, but decreases in some parts of Northern and Southern Europe (Dankers and Feyen, 2008)(Rojas *et al.*, 2012). In contrast, studies of future changes in individual catchments indicate increases in the occurrence of extreme discharges, to varying degrees, in Finland (Veijalainen *et al.*, 2010), Denmark (Thodsen, 2007), Ireland (Wang *et al.*, 2006)(Steele-Dunne *et al.*, 2008)(Bastola *et al.*, 2011), the Rhine basin (Lenderink *et al.*, 2007)(Te Linde *et al.*, 2010a)(Krahe *et al.*, 2009; Hurkmans *et al.*, 2010), the Meuse basin (Leander *et al.*, 2008)(Ward *et al.*, 2011), the Danube basin (Dankers *et al.*, 2007), and French Mediterranean basins (Quintana-Segui *et al.*, 2011). Substantial declines in low flows could occur in the UK (Christierson *et al.*, 2012), as well as in Turkey (Fujihara *et al.*, 2008).

Lack of observational data,and the complex definitions related to different perspectives (meteorological, agricultural, hydrological, socioeconomic) of droughts make the analyses of observed changes in drought characteristics difficult (SREX, Chapter 3, Box 3-3). Southern Europe has experienced trends towards more intense and longer droughts, but they are still inconsistent (Sousa *et al.*, 2011). Drought trends in all other subregions were not statistically significant (SREX chapter 3, section 3.5.1). Regional and global climate simulations project (with medium confidence) an increase in duration and intensity of droughts in central and southern Europe and the Mediterranean region (Gao and Giorgi, 2008; Feyen and Dankers, 2009; Vidal and Wade, 2009)(Tsanis *et al.*, 2011) WG2 Chapter 21) using different definitions of droughts (see also SREX chapter 3, section 3.5.1). In a study by

Wong et al. (Wong *et al.*, 2011) it is shown that even in regions where summer precipitation is expected to increase, soil moisture and hydrological droughts may become more severe due to increasing evapotranspitation.

Figure 23-4 illustrates projected changes the length of dry spells for the period 2071-2100 compared to 1971-2000 (in days) for SRES A1B and RCP4.5. For A1B emission scenariothe projected increase in dry spells is much larger in Southern Europe.

[INSERT FIGURE 23-4 HERE
Figure 23-4: Projected changes in the 95th percentile of the length of dry spells for the period 2071-2100 compared to 1971-2000 (in days) (Jacob et al., 2013). Dry spells are defined as periods of at least 5 consecutive days with daily precipitation below 1mm. For the eastern part of Turkey, unfortunately no regional climate model projections are available. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test). A) Changes represent average over 20 regional model simulations (A1B) taken from EU-ENSEMBLES project. B) Changes represent average over 7 regional model simulations (RCP4.5) taken from EURO-CORDEX project.]

23.3. Implications of Climate Change for Production Systems and Physical Infrastructure

23.3.1. Settlements

New studies since AR4 confirm that European urban areas and related production systems, physical infrastructure and human settlements, are at risk (combination of hazard probability, exposure and vulnerability) from changes in weather extremes, such as flooding, mass movements, and wildfires (see section 23.4.4). Europe currently has a high flood risk, due to the presence of highly urbanised areas in river basins and on coastlines. New studies since AR4 confirm that climate change is likely to increase flooding (coastal, river and pluvial) in Europe in some areas, even with an upgrade of flood defences. Risk assessments have attempted to quantify more policy-relevant outcomes, such as population at risk of flooding and economic damage costs and health and environmental outcomes. New risk assessments have also included economic growth and population growth.

23.3.1.1. Coastal Flooding

Extreme sea level events and coastal flood risk are projected to increase in Europe [Section 23.2.2, SREX report, AR5 WG2 Chapter 5] and remain a key challenge for several major European cities (Nicholls *et al.*, 2008)(Hallegatte *et al.*, 2008)(Hallegatte *et al.*, 2011). Important energy infrastructure, including 158 major oil and gas infrastructure and terminals, and 71 operating nuclear reactors are located at exposed coastal locations (Brown *et al.*, 2013). Climate change may increase the frequency of severe storm surges, particularly in north-western Europe (see Section 23.2.2.3). Upgrading coastal defences would substantially reduce the impacts and damage costs (Hinkel *et al.*, 2010). Without adaptation, the number of people affected by coastal flooding in the 2080s is projected to increase in the range of 775,000 to 5.5 million people per year in the EU27 under the SRES B2 and A2 scenarios (Ciscar *et al.*, 2011). The Atlantic, Northern and Southern European regions are projected to be most affected by coastal floods. Direct costs from sea level rise in the EU27 without adaptation could reach 17 billion Euros per year by 2100 (Hinkel *et al.*, 2010), with wider costs being higher (Bosello *et al.*, 2012). The highest damage costs are estimated for the Netherlands, Germany, France, Belgium, Denmark, Spain and Italy (Hinkel *et al.*, 2010).

Changes in future flood losses due to climate change have also been estimated for Copenhagen (Hallegatte *et al.*, 2011), the UK coast (Mokrech *et al.*, 2008)(Purvis *et al.*, 2008)(Dawson *et al.*, 2011), the North Sea coast (Gaslikova *et al.*, 2011), port cities including Amsterdam and Rotterdam (Hanson *et al.*, 2011), and the Netherlands (Aerts *et al.*, 2008). The increasing cost of insurance and unwillingness of investors to place assets in affected areas is a potential growth impediment to the economy in coastal regions and islands (Day *et al.*, 2008). One study estimated that a 1m sea-level rise in Turkey would potentially affect 3 million additional people and put 12 billion USD capital value at risk, with adaptation costs at around 20 billion (10% of GNP) (Karaca and Nicholls). In Poland, up to 240,000 people would be affected by increasing flood risk on the Baltic coast (Pruszak and Zawadzka, 2008).

23.3.1.2. River and Pluvial Flooding

The observed increased trend in flood disasters and flood damages in Europe is well documented (see 18.4.2.1 for detailed discussion), however, the main cause of the increase is increased exposure of persons and property in flood risk areas (Barredo, 2009). Several new studies provide estimates of the impact of changing precipitation patterns on future economic losses from river flooding, with uncertainties depending on modelling approaches and scenarios (Bubeck *et al.*, 2011). In particular, studies now also quantify the contribution of changes in population and economic growth, generally indicating this contribution to be about equal or larger than climate change per se (Feyen *et al.*, 2009)(Maaskant *et al.*, 2009)(Bouwer *et al.*, 2010)(Te Linde *et al.*, 2011)(Rojas *et al.*, 2012). These studies indicate that some regions may see increasing risks, but others may see decreases or little to no change (Bubeck *et al.*, 2011)(ABI, 2009)(Feyen *et al.*, 2009)(Lugeri *et al.*, 2010)(Mechler *et al.*, 2010)(Feyen *et al.*, 2012)(Lung *et al.*, 2012). A European (EU15) analysis estimated that river flooding could affect 250,000-400,000 additional people by the 2080s, and lead to more than a doubling of annual average damages, with the main increases projected in Central Northern Europe and the UK (Ciscar, 2009)(Ciscar *et al.*, 2011). When economic growth is included with projected flood frequency changes, river flood losses in Europe were projected to increase 17-fold under the A1B scenario (Rojas *et al.*, 2012).

Few studies have estimated future damages from inundation in response to an increase in intense rainfall (Hoes, 2006). Processes that influence flash flood risks include increasing exposure from urban expansion, and forest fires that lead to erosion and increased surface runoff (Lasda *et al.*, 2010). Some studies have costed adaptation measures but these only partly offset anticipated impacts from intense rainfall (Zhou *et al.*, 2012).

23.3.1.3. Mass Movements

Very few studies are available on observed trends or future projections in the frequency of landslides (Crozier, 2010). Landslides are strongly connected to intense precipitations and the local conditions of slope stability. In the European Alps, an apparent increase in the frequency of rock avalanches and large rock slides was documented over the period 1900-2007 (Fischer *et al.*, 2011) and also projected an increase in the frequency for landslides for the future (Huggel *et al.*, 2010), while (Jomelli *et al.*, 2007) and Huggel et al. (Huggel *et al.*, 2012) describe a complex response to climate change. Some land use practices changes have led to increased landslide hazards, counterbalancing favourable climate trends, as reported in Calabria (Polemio and Petrucci, 2010) and in the Apenines (Wasowski *et al.*, 2010). There is a medium confidence that landslides that are related to glacier retreat and temperature will be affected by climate change. The evolution of precipitation driven phenomena such as shallow landslides is rather uncertain because of the difficulty to estimate local precipitation trends with accuracy and other factors such as land use. A study of the Mam Tor landslide in the UK indicated a possible increase in stability towards 2100 in response to rainfall changes (Dixon and Brook, 2007). Climate warming may have contributed to the observed decrease in the frequency of snow avalanches in the Alps (Eckert *et al.*, 2010)(Teich *et al.*, 2012), although one study suggest that conditions for avalanches may become more favourable with warming in the future (Castebrunet *et al.*, 2012).

23.3.2. Housing

Housing infrastructure in Europe is vulnerable to extreme weather events. Despite a wide body of literature on the thermal modelling of the existing housing stock, exactly why and how dwellings currently overheat is uncertain (Crump *et al.*, 2009) and there is very little observational data as to the actual extent of current overheating in countries in Europe. Buildings that were originally designed for certain thermal conditions will need to function in a drier and hotter climate in the future (WHO, 2008). The impact of rising temperatures on comfort (and hence energy demand for cooling and heating) is well understood. Climate change in Europe seems set to result in increased use of cooling energy and reduced use of heating energy. For example, a study of energy demand in Slovenia (Dolinar *et al.*, 2010) projected reductions of energy use for heating of up to 25% depending on the region but up to six times more energy for cooling. More estimates of changes in summer and winter energy demand are described below in

Energy Section, although the assumptions regarding future air conditioning uptake are often not clear. Further, the potential trade-offs and synergies in future energy use for residential heating and space cooling conditioning in the context of future emissions (mitigation) and adaptation is discussed in section 23.8.1 below. A range of adaptive strategies are available to address impacts of climate change on buildings including effective thermal mass and solar shading (Wilby, 2007). There is little evidence regarding the estimated costs of retrofitting European housing stock (Parry *et al.*, 2009).

Climate change may increase the frequency and intensity of drought-induced soil subsidence (Corti *et al.*, 2009). One study indicates that it is likely that the level of damage in France, for example, has more than doubled in the period 1989-2002 compared to the period 1961–1990 (Corti *et al.*, 2009). This is mostly a consequence of increased temperature since the 1990s, suggesting a link to climate change. Some European regions were affected for the first time by soil subsidence following the hot summer of 2003, possibly as a consequence of lack of adaptation.

With respect to the outdoor built environment, there is limited evidence regarding the potential for differential rates of radiatively-forced climate change in urban compared to rural areas (McCarthy *et al.*, 2010). An urban land surface scheme coupled to a global model was used to quantify the impact of large-scale and local drivers of climate change on the urban environment and indicated that these effects should not be treated independently when making projections of urban climate change. Climate change was found to increase the number of 'hot' days by a similar amount for both urban and rural situations but rural and urban increases differed significantly for the frequency of 'hot' nights. Modelling of London's nocturnal heat island indicated an increase in magnitude of urban heat island under project climate scenarios (Wilby, 2008). Modification of the external environment, via enhanced urban greening for example, provides other opportunities for modification of risks and co-benefits for health and welfare.

23.3.3. Transport

Systematic and detailed knowledge on the effects of climate change on transport in Europe remains limited (Koetse and Rietveld, 2009).

On *road transport*, in line with AR4, in case of increased precipitation, an increase in collisions but a decrease of their severity is expected due to reduced speed (Brijs *et al.*, 2008)(Kilpeläinen and Summala, 2007). However, lower traffic speed will cause welfare losses due to additional time spent driving (Sabir *et al.*, 2010). Future severe snow and ice-related accidents will also decrease, but the effect of fewer frost days on total accidents is unclear (Andersson and Chapman, 2011a)(Andersson and Chapman, 2011b). Severe accidents caused by extreme weather are projected to decrease by 54-72% in 2020-2070 compared to 2007 (Nokkala *et al.*, 2012).

For *rail*, consistent with AR4, increased buckling due to higher temperatures, as observed in 2003 in the UK, is expected to increase the average annual cost for heat-related delays in some regions, while opposite effects are expected for ice and snow-related delays (Dobney *et al.*, 2010)(Lindgren *et al.*, 2009). The impacts of extreme precipitation, as well as the net overall regional effect of climate change remain unclear. Efficient adaptation comprises proper maintenance of track and track bed.

Regarding *inland waterways*, the navigability of rivers will be affected. In Rhine, for temperature increases by 1-2 ^{o}C by 2050, high water levels in winter will occur more frequently and, from 2050, days with low water levels during summer will also increase (Jonkeren *et al.*, 2011)(Te Linde *et al.*, 2011)(Te Linde, 2007)(Hurkmans *et al.*, 2010). Future low water levels will imply restrictions on the load factor of inland ships, increasing transport prices, as was the case in the Rhine and Moselle market in 2003 (Jonkeren, 2009)(Jonkeren *et al.*, 2007). Potential adaptation includes modal shift, increased number of navigational hours per day in periods with low water levels and infrastructure modifications (e.g. canalization of river parts) (Jonkeren *et al.*, 2011; Krekt *et al.*, 2011). Using smaller ships could be an attractive option if most barges were not considerably below the optimal size (Demirel, 2011). Regarding *long range ocean transport*, the economic attractiveness of the Northwest Passage and the Northern Sea Route depends also on factors such as passage fees, bunker prices and cost of alternative sea routes (Verny and Grigentin, 2009)(Liu and Kronbak, 2010)(Lasserre and Pelletier, 2011).

On *air transport*, estimates on climate change impacts are very few. Pejovic et al. (Pejovic *et al.*, 2009) found that for London's Heathrow Airport, future temperature and wind changes would have a minor net annual change effect (but much larger seasonal variations), while thunderstorms, snow and fog will increase weather-related delays.

23.3.4. Energy Production, Distribution, and Use

On *wind energy*, no significant changes are expected before 2050 in Northern, part of the Alpine and upper Continental Europe (Pryor and Schoof, 2010)(Pryor and Barthelmie, 2010)(Seljom *et al.*, 2011)(Barstad *et al.*, 2012). After 2050, in line with AR4, sites in these regions may experience a small (<10-15%) increase in energy density (W/m^2) during winter and a decrease in summer (Harrison *et al.*, 2008). For Southern and Atlantic Europe, estimations are more uncertain and present spatial and seasonal variations (Rockel and Woth, 2007)(Bloom *et al.*, 2008)(Najac *et al.*, 2011)(Nolan *et al.*, 2012; Pašičko *et al.*, 2012). The impact of future increases in extreme wind speeds in Northern and Continental Europe (see section 23.2.1) on the operation and maintenance of wind farms remains unclear.

For *hydropower*, Scandinavia will face an increase of power generation up to 14% during 2071-2100 compared to historic or present levels (Golombek *et al.*, 2012)(Johannesson *et al.*, 2012)(Haddeland *et al.*, 2011); for 2021-2050, increases up to 8.5% were estimated, while others predicted increases even by 15-20% (Seljom *et al.*, 2011; Hamududu and Killingtveit, 2012). In Continental and part of Alpine Europe, reductions by 6-46% were estimated, depending on the emission scenario, location and time horizon (Schaefli *et al.*, 2007)(Mauser and Bach, 2009)(Paiva *et al.*, 2011; Pašičko *et al.*, 2012)(Stanzel and Nachtnebel, 2010). For Southern Europe, a decreased production by 5-15% in 2050 compared to 2005 has been estimated (Hamududu and Killingtveit, 2012). Improved water management, including pump storage if appropriate, stands as the main adaptation option (Schaefli *et al.*, 2007)(García-Ruiz *et al.*, 2011).

Biofuel production is covered in section 23.4.6. No literature on climate change impacts on solar energy production was found (since AR4). On *thermal power*, in line with AR4, van Vliet et al. (Van Vliet *et al.*, 2012) estimated a 6-19% decrease of the summer average usable capacity of power plants by 2031–2060 compared to 1971-2000, while lower figures have been also estimated (Linnerud *et al.*, 2011)(Förster and Lilliestam, 2010). Closed-cooling circuits are efficient for adaptation (Koch and Vögele, 2009) but are usually feasible only for new plants. In *power transmission*, increasing lighting faults and decreasing snow-sleet-and blizzard faults for 2050-2080 were estimated for UK (McColl *et al.*, 2012).

By considering both heating and cooling, the *total annual energy demand* in Europe as a whole during 2000-2100 is estimated to decrease following climate change (Isaac and van Vuuren, 2009). Seasonal changes will be prominent, especially for electricity (see Figure 23-5), with summer peaks arising also in countries with moderate summer temperatures (Hekkenberg *et al.*, 2009). Heating degree days under a +3.7 ^{o}C scenario are expected to decrease by 11-20% between 2000 and 2050 due solely to climate change (Isaac and van Vuuren, 2009). For cooling, very large percentage increases up to 2050 are estimated by the same authors for most of Europe as the current penetration of cooling devices is low; then, increases by 74-118% in 2100 (depending on the region) from 2050 are expected under the combined effect of climatic and non-climatic drivers. In the Mediterranean, cooling degree days by 2060 will increase, while heating degree days will decrease but with substantial spatial variations (Giannakopoulos *et al.*, 2009). Following climate change, a net annual increase of future electricity generation cost in most of the Mediterranean and a decrease in the rest of Europe was estimated (Eskeland and Mideksa, 2010)(Mirasgedis *et al.*, 2007)(Pilli-Sihlova *et al.*, 2010; Zachariadis, 2010). Future building stock changes and retrofit rates are critical for impact assessment and adaptation (Olonscheck *et al.*, 2011). Passive-cooling alone may not to be enough, while energy efficient buildings and cooling systems, and demand-side management are effective adaptation options (Artmann *et al.*, 2008; Jenkins *et al.*, 2008; Day *et al.*, 2009; Breesch and Janssens, 2010; Chow and Levermore, 2010).

[INSERT FIGURE 23-5 HERE
Figure 23-5: Percentage change in electricity demand in Greece attributable to climate change, under a range of climate scenarios and economic assumptions. Source: Mirasgedis et al., 2007.]

23.3.5. Industry and Manufacturing

Research on the potential effects of climate change on future consumption patterns (e.g. soft drinks, ice creams) is very limited, and based on current sensitivity to seasonal temperature (Mirasgedis *et al.*, 2013). Climate change may also affect supply chains, utilities and transport infrastructure with implications for some industries (see also chapter 10). Higher temperatures may alter the products' quality and safety by favouring the growth of food borne pathogens or contaminants (Jacxsens *et al.*, 2010; Popov Janevska *et al.*, 2010) (see also section 24.5.1). The production of some high value crops is likely to be affected by climate warming (see 23.4.1 and Box 23-1 on Wine).

23.3.6. Tourism

In line with AR4, in northern areas of Continental Europe, as well as Finland, southern Scandinavia and southern England, climate for general tourist activities especially after 2070 is expected to improve significantly during summer and less during autumn and spring under different emission scenarios (Amelung and Moreno, 2011); (Amelung *et al.*, 2007)(Nicholls and Amelung, 2008), although local weather may not be a major barrier for these activities (Denstadli *et al.*, 2011). For the Mediterranean, climate for light outdoor tourist activities is expected to deteriorate in summer mainly after 2050 but improve during spring and autumn (Amelung and Moreno, 2009) (Hein *et al.*, 2009) (Perch-Nielsen *et al.*, 2010)(Amelung *et al.*, 2007)(Giannakopoulos *et al.*, 2011). Though, other studies concluded that before 2030 (or even 2060) this region as a whole will not become too hot for beach or urban tourism (Moreno and Amelung, 2009)(Rutty and Scott, 2010). Observed visitation data and questionnaires indicate that beach tourists are not deterred by moderately high temperatures but by rain (De Freitas *et al.*, 2008)(Moreno, 2010)(Moreno and Amelung, 2009). Tourist arrivals depend also on the age of tourists and the climate at their country of origin, economic and environmental conditions at destinations (e.g. water stress, increased further by climate change and tourist development) (Hamilton and Tol, 2007)(Moreno and Amelung, 2009; Perch-Nielsen *et al.*, 2010)(Lyons *et al.*, 2009; Eugenio-Martin and Campos-Soria, 2010)(Rico-Amoros *et al.*, 2009). The future capacity of accommodation and transport networks in destinations is also important.

Regarding ski tourism, in agreement with AR4, climate change will affect natural snow reliability and consequently the ski season's length, especially in cases without or limited artificial snowmaking (OECD, 2007)(Steiger, 2011)(Steiger, 2010b)(Moen and Fredman, 2007). Low-lying areas will be the most vulnerable (Uhlmann *et al.*, 2009; Endler *et al.*, 2010; Serquet and Rebetez, 2011; Steiger, 2011; Endler and Matzarakis, 2011a). The response of tourists to marginal snow conditions remains largely unknown (Scott et al., 2012), while changes in weather extremes may also be critical (Tervo, 2008). Up to mid-century, demographic changes may have a higher impact on skiing tourism than climate change (Steiger, 2012). Artificial snowmaking has physical and economic limitations, especially in small/ medium sized and low-altitude ski stations (Sauter *et al.*, 2010)(Steiger, 2010a; Steiger, 2010b)(Steiger and Mayer, 2008), and increases water and energy consumption. Other options may include shift to higher altitudes, operational changes, technical measures and year-round tourist activities, although it is still uncertain whether they can fully compensate climate change adverse impacts. Mountainous areas may face improved climatic conditions for summer tourism due to climate change (Endler *et al.*, 2010; Perch-Nielsen *et al.*, 2010; Serquet and Rebetez, 2011; Endler and Matzarakis, 2011b).

23.3.7. Insurance and Banking

The financial sector has a large base in Europe, and its global and regional activities are potentially affected by climate change (see AR5 WG2 Section 10.7 for a more detailed discussion). The insurance and banking sector is affected by problems with accurate pricing of insurance, shortage of capital after large loss events (weather disasters), and by an increasing burden of losses that can affect markets and insurability, within but also outside the European region (CEA, 2007; Botzen *et al.*, 2010a; Botzen *et al.*, 2010b). On the other hand, risk transfer mechanisms including insurance are also an important means to cover and reduce losses from extreme weather (Botzen and van den Bergh, 2008; CEA, 2009)(Herweijer *et al.*, 2009).

Banking is potentially affected through physical impacts from climate change on their assets and investments, as well as regulation and/or through mitigation actions by changing demands regarding carbon emissions from activities related to their investments and lending portfolios. Few banks have adopted climate strategies that also address adaptation (Furrer *et al.*, 2009)(Cogan, 2008).

Windstorm losses that are generally well covered in Europe by building and motor policies and create a large exposure to the insurance sector. Studies indicate an overall increase storm hazard (see Section 23.2.2.3) and possibly insured losses (see Chapter 17.7.3 for a full discussion), but the natural variations in storm frequency are large. There is no evidence that the increase in historic European storm damages is due to anthropogenic climate change. The increasing number and value of buildings and infrastructure is a major driver at present (Barredo, 2010). Flood losses in the UK in 2000, 2007 and 2009 have put the insurance market under further pressure, with increasing need for the government to reduce risk (Ward *et al.*, 2008)(Lamond *et al.*, 2009). Other losses of concern to the European insurance industry are building subsidence losses related to drought (Corti *et al.*, 2009), insured hail damage to buildings (Kunz *et al.*, 2009) (Botzen *et al.*, 2010b)(GIA, 2011).

The financial sector can adapt through adjustment of premiums, restricting or reduction of coverage, further risk spreading, and importantly incentivising risk reduction (Clemo, 2008; Botzen *et al.*, 2010a)(Crichton, 2007)(Crichton, 2006)(Wamsler and Lawson, 2011)(Surminski and Philp, 2010). Willingness-to-pay studies in Scotland and the Netherlands show that public attitudes would support insurance of private property and public infrastructure damages in the case of increasing flood risk (Botzen *et al.*, 2009)(Glenk and Fisher, 2010). Government intervention is needed in many European countries to provide compensation and back-stopping of private insurance schemes in the event of major losses (Aakre and Rübbelke, 2010; Aakre *et al.*, 2010). Hochrainer *et al.* (Hochrainer *et al.*, 2010; Hochrainer *et al.*, 2010) analysed the performance of the EU Solidarity Fund system that supports European governments in the event of large losses, and argue there is a need to shift its focus from compensation to incentivising risk reduction. Alternative forms of private insurance mechanisms, such as long-term (multi-year) contracts for European flood risks suffer from uncertainty related to future risks under climate change, leading to additional risk to private insurance firms (Aerts and Botzen, 2011).

23.4. Implications of Climate Change for Agriculture, Fisheries, Forestry and Bioenergy Production

23.4.1. Plant (Food) Production

In AR4, Alcamo et al. (2007) reported that crop suitability is *likely* to change throughout Europe, and crop productivity (all other factors remaining unchanged) is *likely* to increase in Northern Europe, and decrease in Southern Europe, and the eastern part of Continental Europe.

The frequency and severity of climatic extremes affect agricultural systems (Tubiello *et al.*, 2007)(Coumou and Rahmstorf, 2012) Table 23-5). Climate-induced variability in wheat production has increased in recent decades in France, Italy and Spain (Brisson *et al.*, 2010)(Hawkins *et al.*, 2013) and in some Hungarian regions (Ladanyi, 2008), while in the northernmost agricultural areas of Europe, no consistent reduction in yield variability was recorded despite warming (Peltonen-sainio *et al.*, 2010). In 2003 and 2010, Western Europe and Western Russia, respectively, experienced their hottest summers since 1500 (Luterbacher *et al.*, 2004)(Barriopedro *et al.*, 2011); grain-harvest losses in affected regions reached 20 and 30%, respectively (Ciais *et al.*, 2005; Aerts and Botzen, 2011; Aerts and Botzen, 2011). The 2004/2005 hydrological year was characterised by an intense drought throughout the Iberian Peninsula and cereals production fell on average by 40% (EEA, 2010b). In 2011, the hottest and driest spring on record in France since 1880 reduced annual grassland production and annual grain harvest by 20 and 12%, respectively (AGRESTE, 2011)(Coumou and Rahmstorf, 2012). In the Czech Republic, the grain yield sensitivity to a 1◦C temperature increase during the growing season was -11% and -10% for winter wheat and spring barley, respectively, over 1961-2007 (Trnka *et al.*, 2012).

In many European countries cereal yields have declined in recent decades (Olesen *et al.*, 2011) although the national statistical yields are below the agro-climatic potential yield (Supit *et al.*, 2010). Cereal yields have been negatively affected by warming in some European countries since 1980, for example, in France by -5% for wheat and -4% for

maize (Lobell *et al.*, 2011). Restricted crop inputs and changes in crop rotations, as well as the increased frequency of high temperatures and droughts during grain filling, have reduced wheat yield growth in France (Brisson *et al.*, 2010; Kristensen *et al.*, 2011). In contrast, in eastern Scotland, warming is estimated to have contributed to 23–26% of observed increase potato yields since 1960 (Gregory and Marshall, 2012). In North-East Spain, an increased water deficit in the reproductive stage since the 1960s has reduced grape yield by up to 30 kg/ha per millimetre (Camps and Ramos, 2012). This is consistent with agro-climatic modelling showing a widespread decline over the period 1976-2005 in the climatic potential of crop yields, especially in Italy, central and eastern Europe (Supit *et al.*, 2010).

Insight into the potential effect of climate change on any particular species or crop system requires the combination of a wide range of emission scenarios, global circulation models (GCM) and impact studies (Trnka *et al.*, 2007)(Soussana *et al.*, 2010). For a global temperature increase of 5° C, agroclimatic indices adjusted to reflect the effects of atmospheric CO_2 concentration on evapotranspiration and based on outputs from three GCMs, show increased drought stress and shortening of the active growing season with an increasing number of extremely unfavourable years in a number of European regions (Trnka *et al.*, 2011). In the EU27, a 2.5 °C temperature increase in the 2080s could lead to small changes in crop yields, whereas a 5.4 °C scenario could reduce yields by 10% (Ciscar *et al.*, 2011). A study combining three GCMs and two emission scenarios (B1 and A2) with a weather generator and the crop modelling system GCMS applied to wheat, maize and sugar beet, and assuming neither impacts by weeds, pests and diseases nor limitations by nutrients, indicates an initial benefit from the increasing CO_2 concentration for rainfed crop yields in most European regions, contrasting by the end of the century with yields declines in most regions (Supit *et al.*, 2012). Under the A2 scenario, wheat yield is projected to increase at the end of the century compared to the baseline period 1990–2008 (Supit *et al.*, 2012). Another study, using the CropSyst model and bias-corrected downscaled simulations for the A1B emission scenario, shows based on outputs from the HadCM3 GCM, that disease (wheat leaf rust and corn grey leaf spot) limited yields of rainfed wheat and maize would be reduced despite the increase in atmospheric CO_2 by 5-20% in ca. half of the European cropping area in the 2030's compared to a reference period centred on the year 2000, while the corresponding yield changes would be non-significant or slightly positive based on the ECHAM GCM (Donatelli *et al.*, 2012).

The regional distribution of climate change impacts on agricultural production is *likely* to vary widely (Iglesias *et al.*, 2012)(Donatelli *et al.*, 2012), Figure 23-6). Southern Europe would experience the largest yield losses that would reach about 25 % by 2080 under a 5.4 °C temperature increase (Ciscar *et al.*, 2011). Conditional on increased water shortage and extreme weather events (heat, drought) rainfed summer crop failure is *very likely* to rise sharply (Bindi and Olesen, 2011)(Ferrara *et al.*, 2010)(Ruiz-Ramos *et al.*, 2011) in Southern Europe. The Central Europe regions would experience moderate declines in crop yields (Ciscar *et al.*, 2011), as a result of warmer and drier conditions by 2050 (Trnka *et al.*, 2010; Trnka *et al.*, 2011). In Western Europe, for the 2050s, increased heat stress around flowering is *likely* to increase significantly in wheat which may result in considerable yield losses (Semenov, 2009).

For Northern Europe, there is diverging evidence concerning future impacts. Positive yield changes combined with the expansion of climatically suitable areas could lead to crop production increases for a large range of scenarios (between 2.5 and 5.4°C warming) (Bindi and Olesen, 2011). However, at high latitudes, even accounting for the positive effects of CO_2 fertilization, impacts on cereal production could become negative with a high risk of marked yield loss beyond 4°C global temperature increase (Rötter *et al.*, 2011). Increased climatic variability would limit winter crops expansion in the northernmost agricultural areas of Europe (Peltonen-sainio *et al.*, 2010), but spring crops from tropical origin like maize for silage could become cultivated in Finland by the end of this century (Peltonen-Sainio *et al.*, 2009).

[INSERT FIGURE 23-6 HERE
Figure 23-6: Percentage change in simulated water-limited yield for winter wheat in 2030 with respect to the 2000 baseline under the A1B scenario as modelled using ECHAM5 (left column) and HadCM3 (right). Upper maps to do not take adaptation into account whereas the bottom maps show the result for the best adaptation strategy for cell (Source: Donatelli et al. 2012).]

Ozone is the most important air pollutant that affects agricultural production. For the European Union, compared to a baseline without crop injuries from ozone, wheat and maize yield reduction from ozone were estimated at 7% in 2000 and would reach 6 and 10 % in 2030 for the B1 and A2 scenarios, respectively (Avnery *et al.*, 2011a; Avnery *et al.*, 2011b). Crop sensitivity to ozone tends to decline with increasing atmospheric CO_2 and in areas where warming is accompanied by drying, such as southern and continental Europe. In contrast, the ozone sensitivity of crops would remain high at higher latitudes the absence of declining air and soil moisture (Fuhrer, 2009).

Some economically damaging weeds, such as the shallow rooted *Alopecurus myosuroides* in UK, could become less competitive with wheat owing to more frequent and severe drought stress events under climate change that favour deeper rooted crop plants such as wheat (Stratonovitch, 2012). However, deep rooted weeds (Gilgen *et al.*, 2010) and weeds with contrasting physiology, such as C_4 species, may become better adapted to future conditions and pose a more serious threat (Bradley *et al.*, 2010).

For crops remaining in their original geographical range, generally warmer conditions would exacerbate arthropod-borne diseases (many viruses and phytoplasmas) and those root and stem diseases that first infect hosts during the autumn and winter, such as stem canker of oilseed rape and eyespot of wheat (West *et al.*, 2012). Rising temperatures during the vegetation period, enhances the appearance of a black rot fungus in fruit trees of Northwestern Europe, but this does not hold for other fruit rot species (Weber, 2009) and some pathogens like cereal stem rots (e.g. *Puccinia striiformis*) (Luck *et al.*, 2011) and grapevine powdery mildew (Caffarra *et al.*, 2012) could be limited by increasing temperatures. By the 2050s, more severe *Fusarium* blight epidemics are projected in southern England (Madgwick *et al.*, 2011), while the European corn borer (*Ostrinia nubilalis*) would extend its climate niche in Central Europe (Trnka *et al.*, 2007). Increased damages from plant pathogens and insect pests are projected by 2050 in Nordic countries which have hitherto been protected by cold winters and geographic isolation (Hakala *et al.*, 2011; Roos *et al.*, 2011). Yield losses from phoma stem canker epidemics could increase to up to 50 per cent in South England and greatly decrease yield of untreated winter oilseed rape (Butterworth *et al.*, 2010). Increasing temperatures might have a detrimental impact on grapevine yield due to increased asynchrony between larval development of the European grapevine moth and the larvae-resistant growth stages of grapevine (Caffarra *et al.*, 2012). Disease management will also be affected with regard to timing, preference and efficacy of chemical, physical and biological measures of control and their utilization within integrated pest management strategies (Kersebaum *et al.*, 2008).

Farmers across Europe are currently adapting to climate change (Olesen *et al.*, 2011). Simple, no-cost adaptation options such as advancement of sowing and harvesting dates or the use of longer cycle varieties may be implemented although such options may become less successful in a more variable climate (Moriondo *et al.*, 2010; Moriondo *et al.*, 2011)(Howden *et al.*, 2007). Such "autonomous" adaptation by farmers could result in a general improvement of European wheat yields in the 2030s compared to the 2000s (Donatelli *et al.*, 2012) (Figure 23-6). However, earlier sowing is often prevented by lack of soil workability and frost-induced soil crumbling (Oort, 2012). Observations suggest that farmer sowing dates are advancing slower (e.g. by only 0.2 days per decade over the last 50 years, (Siebert and Ewert, 2012) than crop phenology (Menzel *et al.*, 2006)(Siebert and Ewert, 2012)(Oort, 2012) in Europe. Simulation studies which anticipate on earlier sowing may thus be overly optimistic.

Further adaptation options include: changes in crop species, fertilization, irrigation, drainage, land allocation and farming system (Bindi and Olesen, 2011). In South Italy, for a global mean temperature change of 2°C (above pre-industrial levels), adaptation measures (irrigation and fertilization) would alleviate the negative effects of climate change on crop (tomato and durum wheat) productivity (Ventrella *et al.*, 2012). At the high range of the projected temperature changes, only plant breeding aimed at increasing yield potential jointly with drought resistance and adjusted agronomic practices, such as sowing and adequate nitrogen fertilizer management, may reduce risks of yield shortfall (Olesen *et al.*, 2011)(Rötter *et al.*, 2011)(Ventrella *et al.*, 2012). Climate change alters breeding targets. The identification of the most CO_2-responsive genotypes (Ainsworth *et al.*, 2008) and of heat, drought- and salinity-tolerant genotypes (Tester and Langridge, 2010)(Semenov and Shewry, 2011) as well as the preservation of the option value provided by plant genetic diversity, is a pre-requisite to provide starting lines for breeding programmes (Jump *et al.*, 2009). However, crop breeding is challenged by temperature and rainfall variability, since: i) breeding has not yet succeeded in altering crop plant development responses to short-term changes in

temperature (Parent and Tardieu, 2012) and ii) distinct crop drought tolerance traits are required for mild and severe water deficit scenarios (Tardieu, 2012).

Achieving increased adaptation action will necessitate integration of climate change-related issues with other risk factors, such as market risk (Howden *et al.*, 2007)(Knox *et al.*, 2010). Adaptation to increased climatic variability may imply an increased use of between and within species genetic diversity in farming systems (Smith and Olesen, 2010). The development of insurance products against weather-related yield variations by using precipitation options (Musshoff *et al.*, 2011) may be a tool to reduce risk aversion by farmers. Adaptive capacity to variable and changing conditions is largely attributable to the characteristics of farm types (Reidsma *et al.*, 2009) which may vary given long-term farm structural change induced by climate change (Mandryk *et al.*, 2012). The long term economic viability of farming systems under future scenarios is better characterised by combining ecological and economic optimisation models at the farm scale (Moriondo *et al.*, 2010b).

23.4.2. Livestock Production

Livestock production is impacted by heat. High temperatures lead to a reduction in animal voluntary intake and put a ceiling on dairy milk yield from feed intake (Tubiello *et al.*, 2007). For intensive dairy systems in the Netherlands, heat stress affected dairy production above a daily mean temperature of 18 degrees C (André *et al.*, 2011). For finishing pigs, a meta-analysis shows that growth performance decreases at an accelerating rate when daily temperature increases above a threshold comprised between 21 and 30° (Renaudeau *et al.*, 2011). With dairy cattle in Italy, the mortality risk increased by 60% as a result of exposure during breeding to a combination of high air temperature and air humidity (Crescio *et al.*, 2010). For domesticated animals, climate change adaptation involves changes in diets and farm buildings (Renaudeau *et al.*, 2012) as well as genetic improvement programmes targeting adaptive and performance traits in locally adapted genotypes (Hoffmann, 2010).

Atmospheric CO_2 rise, warming and altered precipitation patterns may change the amount timing and quality of forage production in Europe (Soussana and Luscher, 2007). Experimental manipulation shows the resilience of semi-natural grassland vegetation to prolonged experimental heating and water manipulation (Grime *et al.*, 2008). Nevertheless, even under elevated CO_2, annual grassland production in a French upland site was significantly reduced by four years exposure to climatic conditions corresponding to the A2 emission scenario for the 2070s (Cantarel *et al.*, 2013). Repeated exposure of grasslands to summer droughts increased weed pressure by tap rooted forbs such as *Rumex* (Gilgen *et al.*, 2010). With grass based dairy systems, simulations under the A1B scenario with an ensemble of downscaled GCMs show by the end of the century increases in potential dairy production in Ireland and France, however with increasing risks of summer-autumn forage production failures at French sites (Fitzgerald *et al.*, 2010; Graux *et al.*, 2012) . In continental Europe, grass based dairy systems could suffer from rising water deficits and forage yield variability (Trnka *et al.*, 2009). With sown forage grasses, Mediterranean populations were more resilient than temperate populations to soil water deficit and to heat (Poirier *et al.*, 2012) and could therefore be used to breed better adapted plant material.

The spread of bluetongue virus (BTV) in sheep across Europe has been partly attributed to climate warming (Arzt *et al.*, 2010)(Guis *et al.*, 2012) and was caused by increased seasonal activity of the *Culicoides* vector (Wilson and Mellor, 2009). Climate change is unlikely to extend the distribution of vector *Culicoides imicola* but may increase its abundance in Southern Europe (Acevedo *et al.*, 2010). Ticks, the primary arthropod vectors of zoonotic diseases in Europe, have *likely* changed distributions with climate warming (van Dijk *et al.*, 2010)(Randolph and Rogers, 2010; Petney *et al.*, 2012)(23.5), Climate warming may also increase the risk of fly strike incidence but this can be managed through changes in husbandry practices (Wall and Ellse, 2011). For Europe, climate change is not project to increase by the 2080s the overall risk of incursion of Crimean-Congo haemorrhagic fever virus in livestock through infected ticks introduced by migratory bird species (Gale *et al.*, 2012). The probability of introduction and large-scale spread of Rift Valley Fever in Europe is also very low (Chevalier *et al.*, 2010). Epidemiological surveillance and increased coordinated regional monitoring and control programmes have the potential to reduce the incidence of vector-borne animal diseases (Chevalier *et al.*, 2010)(Wilson and Mellor, 2009).

23.4.3. Water Resources and Agriculture

Future projected trends confirm (Falloon and Betts, 2010) the widening of water resource differences between Northern and Southern European regions reported in AR4 (Alcamo *et al.*, 2007). Under the A1B scenario multi-model simulations show for the 21st century that Nordic river basins have the highest probability of exceeding past high flows during winter, while in Central and Southern European basins the probability of reduced low flows in summer is highest (Weiss, 2011). Simulations using ensemble of GCMs and regional climate models under the A2 emission scenario, show significant reductions by the end of the century in groundwater recharge and/or water table level for river basins located in Northern France (Ducharne *et al.*, 2010), Belgium (Goderniaux *et al.*, 2011), Southern Italy (Senatore *et al.*, 2011) and Spain (Guardiola-Albert and Jackson, 2011), while non-significant impacts were found for aquifers in Switzerland and in England (Stoll *et al.*, 2011)(Jackson *et al.*, 2011). In Northern Europe, negative impacts on water quality are expected due to the intensification of agriculture (Bindi and Olesen, 2010). In the Seine river basin, even with reduced N fertilizer application, groundwater nitrate concentrations would increase during the 21st century (Ducharne *et al.*, 2007). Changes in seasonal precipitation distribution, such as less precipitation in summer and higher rainfall during winter, can enhance nitrate leaching due to lower nitrogen use efficiency in dry periods with higher residual mineral nitrogen after harvest and increased percolation during winter (Kersebaum *et al.*, 2008).

Projections in most European regions, show deteriorating agroclimatic conditions and reduced suitability for rainfed agricultural production (Daccache *et al.*, 2012)(Trnka *et al.*, 2011)(Daccache and Lamaddalena, 2010)(Henriques *et al.*, 2008). Water demand for crop irrigation is projected increase by 40 to 250% by 2100, depending on the crop, in the Fluvià watershed (Catalonia, NE Spain) under the B1 and A2 scenarios (Savé *et al.*, 2012).

Increased irrigation may, however, not be a viable option in a number of European regions because of the reduction in total runoff and of declining groundwater resources, especially in the Mediterranean area (Olesen *et al.*, 2011). Supplementary irrigation in central and eastern England would be constrained by water availability, since in the corresponding catchments water resources are already over-licensed and/or over-abstracted (Daccache *et al.*, 2012). In the French Beauce region, one of the hotspots for irrigation in Europe, water resources reliability is threatened by climate change induced decline in groundwater recharge and to a lesser extent by the increase in potential demand for irrigation (Ducharne *et al.*, 2010). For a tributary of the Ebro river in Spain, drying is projected to occur mainly during the summer with a reduction in the amount of water available for irrigation, due to projected seasonal reductions in reservoir levels (Majone *et al.*, 2012). The need for irrigation may also appear in regions without irrigation infrastructure, as observed during the 2003 summer heat wave and drought in France (van *et al.*, 2010). In Southern Italy, climate change could increase the number of failures for current irrigation systems up to 54-60%. System costs would increase by 20-27% when designed according to the future irrigation demand (Daccache and Lamaddalena, 2010). Even though the adoption of irrigation leads to higher and less variable crop yields in the future, economic benefits of this adoption decision are expected to be rather small. Thus, without changes in institutional and market conditions, no adoption is expected in countries like Switzerland (Finger *et al.*, 2011).

For Northern Europe, agricultural adaptation may be shaped by increased water supply and flood hazards. The need for effective adaptation will be greatest in Southern and south-eastern regions of Europe which already suffer most from water stress, as a result of increased production vulnerability, reduced water supply and increased demands for irrigation (Trnka *et al.*, 2009)(Falloon and Betts, 2010). High frequency of rainy conditions complicates soil workability (Olesen *et al.*, 2011). Earlier sowing dates may allow earlier irrigation and a reduction of the water application (Gonzalez-Camacho *et al.*, 2008). An increased soil organic matter content may facilitate better soil water retention during drought and enhance infiltration capacities (Lee *et al.*, 2008). Areas with poor water-holding soils could be managed extensively for groundwater recharge harvesting, while better water-holding soils could be used for high input crop production (Wessolek and Asseng, 2006). Improved water management in upstream food production areas could mitigate adverse impacts downstream (Kløve *et al.*, 2011). Alternative options such as the use of low-energy systems, improving irrigation efficiency, switching to deficit irrigation and changing cropping patterns to increase water use efficiency can be used as adaptation pathways (Daccache and Lamaddalena, 2010)(Schutze and Schmitz, 2010).

Water use by agriculture affects aquatic ecosystems through stream flow reduction, alteration in stream flow patterns, wetland degradation and declining water quality. Terrestrial ecosystems are affected through changes in groundwater levels and alterations to runoff due to land use changes (Kløve *et al.*, 2011). Under economically focussed regional futures, water supply availability increases at the expense of the environment. Under environmentally focussed futures, irrigation demand restrictions are imposed. In a global market-drive future irrigation demand is price sensitive and has an impact on the type of crops under all climate scenarios (Henriques *et al.*, 2008). More bioenergy production may result in more water stress in some river basins and regions, in particular in southern Europe and during dry summers (Dworak *et al.*, 2009).

23.4.4. Forestry

Observed and future responses of forests to climate change include changes in growth rates, phenology, species composition, increased fire and storm damage, and increased insect and pathogen damage.

Forest growth and phenology

Tree mortality and forest decline due to severe drought events were observed in forests populations in many Mediterranean countries (Affolter *et al.*, 2010)(Bigler *et al.*, 2006; Raftoyannis *et al.*, 2008) as Italy (Bertini *et al.*, 2011)(Giuggiola *et al.*, 2010), Cyprus (ECHOES Country report, 2009), Greece (Raftoyannis *et al.*, 2008) and in the pre-Alps in France (Rouault *et al.*, 2006; Allen *et al.*, 2010)(Nageleisen, 2008; Giuggiola *et al.*, 2010) not only in arid regions but also in wet forests not normally considered at risk of drought (Choat *et al.*, 2012). Phenological advancement in the leaf bud burst and flowering timing was recorded in deciduous species of Southern and Central Finland (Linkosaloa *et al.*, 2009) and crown defoliation was observed in southern European forests due to climate change during 1987-2007 (Carnicer *et al.*, 2011). Despite such negative trends, an increase in forest productivity was observed since 1986 in Italian mountain beech due to the increase of average temperatures (Rodolfi *et al.*, 2007).

Climate change will affect growth and regeneration of forest tree populations in Europe (Lavalle et al., 2009). Future projections show that in Northern and Atlantic Europe the increasing atmospheric CO_2 and warmer temperatures are expected to result in positive effects on forest growth and wood production, at least in the short–medium term (Lindner *et al.*, 2010). On the other hand, in Southern and conitnental Europe increasing drought and disturbance risks will cause adverse effects and productivity is expected to decline (Lindner *et al.*, 2010). The CO_2 fertilization in both Central Europe and Mediterranean will have positive effects on growth although these results contrast with habitat reductions and decline of stand regeneration (Hlásny *et al.*, 2011; Keenan *et al.*, 2011; E Silva *et al.*, 2012).

Species composition

Shifts in forest tree species range due to climate change has been predicted by model-based projections for the period 2070-2100, with a general trend of a south-west to north-east, under A1B scenario, and uphill shifts in suitable habitats for forest categories (Feehan *et al.*, 2009)(Casalegno *et al.*, 2007) causing large ecological and socio-economic impacts and becoming an important issue to be addressed for forest management (Giuggiola *et al.*, 2010; Hemery *et al.*, 2010; García-López J.M. and Alluéa, 2011). By 2100 climate change is expected to reduce the economic value of European forest land by 14 to 50 % under A1B climate scenario, which equates to a potential damage of several hundred billion Euros unless effective countermeasures are taken, owing to the decline of economically valuable species (Hanewinkel *et al.*, 2012).

Fire and storm damage

In Southern Europe, fire frequency and fire extent significantly increased due to climate change in recent decades especially in the Mediterranean basin (Marques *et al.*, 2011; Pausas and Fernández-Muñoz, 2012) including an expansion of fire-prone areas (Fernandes *et al.*, 2010; Koutsias *et al.*, 2012) and a lengthening of the fire season (Lavalle *et al.*, 2009; Albert and Schmidt, 2010). Extreme weather events (drought, heat waves and strong winds) increased the incidence of forest fires in Southern Europe (Camia and Amatulli, 2009; Hoinka *et al.*, 2009; Carvalho *et al.*, 2011; Koutsias *et al.*, 2012; Salis *et al.*, 2013). The most severe events in France, Greece, Italy, Portugal, Spain, and Turkey in 2009 were associated with strong winds that spread fires during a hot, dry period (see also

(EEA, 2008). However, the observed fire trend is also attributable to changes in land use (Marlon *et al.*, 2008; Carmo *et al.*, 2011), socio-economic development and fire-policy factors (Martinez-Casasnovas and Ramos, 2009; Romero-Calcerrada *et al.*, 2010; Koutsias *et al.*, 2012; Pausas and Fernández-Muñoz, 2012; {{1545 Pezzatti 2011;}}.

Fire is expected to become more prevalent also in the future due to climate change causing negative effects on forest ecosystems and significant emissions of greenhouse gases due to biomass burning (Pausas *et al.*, 2008; Vilén and Fernandes, 2011; Chiriacò *et al.*, 2013), even if often difficult to precisely quantify (Chiriacò *et al.*, 2013). The future climate change impacts on forest fires in Mediterranean basin might depend on the balance between higher flammability due to warmer and drier conditions, socio-economic drivers and landscape planning to reduce fuel loads and fire hazard (Moreira *et al.*, 2011). The fire risk is projected to increase in the Mediterranean region (Lindner *et al.*, 2010; Carvalho *et al.*, 2011; Dury *et al.*, 2011; Vilén and Fernandes, 2011) with increase in the occurrence of high fire danger days (Moreno and Amelung, 2009; Arca *et al.*, 2012) and in fire season length (Pellizzaro *et al.*, 2010). The annual burned area is projected to increase by a factor of 3 to 5 in the Mediterranean area compared to the present under the A2 scenario by 2100 (Dury *et al.*, 2011). In Northern Europe, fires are projected to be less frequent due to increased humidity (Rosan and Hammarlund, 2007).

The most severe damage to forests in Central Europe occurs during winter storms caused by Northern Hemispheric mid-latitude cyclones. Increasing growing stock, warm winter temperature and high precipitation, increasing maximum gust wind speed have contributed to the recent increase in windstorm damage to forests (Usbeck *et al.*, 2010). The future storm tracks may shift further north with the consequent possibility of increased risk of damage. Boreal forests will get more vulnerable to autumn/early spring storm damage due to expected decrease in period of frozen soil (Gardiner *et al.*, 2010). Increased storm losses by 8-19% under A1B and B2 scenarios respectively is projected in Western Germany for 2060-2100 compared to 1960-2000, with the highest impacts in the mountainous regions (Pinto *et al.*, 2010; Klaus *et al.*, 2011).

[INSERT FIGURE 23-7 HERE
Figure 23-7: Projected fire risk in Europe for two time periods (2011–2040 and 2041–2070) based on high-resolution regional climate models from the ENSEMBLES project under the SRES A1B emission scenario.]

Insect and pathogen damage

Many opportunist fungi and insects benefit from climate change both directly, because of the survival of a greater number of individuals, and indirectly, because of the changes induced in host phenology (Slippers and Wingfield, 2007). A development of diseases caused by thermophilous pathogens was observed in many European forests (Marcais and Desprez-Loustau, 2007). In temperate zones of Continental Europe, fungi are even more problematic damage agents than insects, with some species that benefit from milder winters and others that spread during drought periods from south to north (Drenkhan *et al.*, 2006; Hanso and Drenkhan, 2007). Projected increased late summer warming events will favour a second generation of bark beetle in southern Scandinavia and a third generation in lowland parts of central Europe (Jönsson *et al.*, 2011). Spruce bark beetle will be able to initiate a second generation in South Sweden during 50% of the years around the mid century and in 63-81% of the years at the end of the century under A2, A1B and B2 scenarios (Jönsson *et al.*, 2009). Bark beetle damages in Austrian spruce forests are projected to double until 2100 assuming no adaptation measures (Seidl *et al.*, 2009).

Forest management and land use

Projected shortening frost periods and thawing permafrost may strongly reduce the accessibility of forests in the Boreal zone with implications for the timber supply (Keskitalo, 2008). Climate change together with socio-economic and technological drivers will influence future European land use leading to declines in the agricultural area and increase in forested and urban areas that would potentially reduce GHG emissions and enhance carbon sinks (Rounsevell and Reay, 2009). Possible response approaches to the impacts of climate change on forestry include short-term and long-term strategies that focus on enhancing ecosystem resistance and resilience (Millar *et al.*, 2007). Fragmented small-scale forest ownership can constrain adaptive capacity (Lindner *et al.*, 2010). Forest management with thinning and shrub removal could decrease competition for water and increase carbon uptake. (Giuggiola *et al.*, 2010). Ongoing changes in species composition from conifers to broadleaves and increasing harvest level might lower the vulnerability through reduction of share of old and vulnerable stands (Schelhaas *et al.*,

2010). Strategies to anticipate severe forest mortality in the future include preference of species better adapted to relatively warm environmental conditions (Resco *et al.*, 2007). The selection of tolerant or resistant families and clones may also reduce the risk of damage by pests and diseases in pure stands (Jactel *et al.*, 2009).

23.4.5. Bioenergy Production

Climate change is *likely* to change the distribution of key bioenergy crops. Dedicated crops for bioenergy in temperate regions, including tree species grown as short rotation coppice (SRC) and intensive forestry, and C4 grasses such as Miscanthus and switchgrass, will respond to climate change by shifting their potential distribution and altering their potential productivity and yields. The potential distribution of temperate oilseeds (e.g. oilseed rape, sunflower), starch crops (e.g. potatoes), cereals (e.g. barley) and solid biofuel crops (e.g. sorghum, Miscanthus) is predicted to increase in northern Europe by the 2080s, due to increasing temperatures, and decrease in southern Europe due to increased drought. Mediterranean oil and solid biofuel crops, currently restricted to southern Europe, are predicted to extend further north due to higher summer temperatures. Four global climate models, (HadCM3, CSIRO2, PCM and CGCM2) predict that bioenergy crop production in Spain is especially vulnerable to climate change, with many temperate crops predicted to decline dramatically by the 2080s. The choice of bioenergy crops in southern Europe will be severely reduced in future unless measures are taken to adapt to climate change (Tuck *et al.*, 2006).

The physiological responses of bioenergy crops C3Salicaceae trees and C4 grasses to rising atmospheric CO_2 concentration would improve drought tolerance due to improved plant water use, consequently yields in temperate environments may remain high in future climate scenarios (Oliver *et al.*, 2009). A future increase in potential biomass production due to elevated CO_2 outweighs the increased production costs resulting in a northward extension of the area where SRC is greenhouse gas neutral (i.e. it produces exactly the amount of biomass that is required to have the avoided emissions compensate for the total emissions from crop management and bio-energy production). However, the northward expansion of SRC would erode the European terrestrial carbon sink due to intensive management and high turnover of SRC respect to conventional forest where usually harvesting is less than annual growth (Liberloo *et al.*, 2010).

23.4.6. Fisheries and Aquaculture

In AR4, Easterling *et al.* (2007) reported that the recruitment and production of marine fisheries in the North Atlantic are *likely* to increase. Warming induces a shift of species ranges toward higher latitudes and seasonal shifts in life cycle events (Daufresne *et al.*, 2009) (see also 23.6.4). In European seas, warming causes a displacement to the north and/or in depth of fish populations. These displacements of species distribution areas have a direct impact on fisheries (Rosenzweig *et al.*, 2008)(Tasker, 2008)(Cheung *et al.*, 2009; Cheung *et al.*, 2010). A widespread reduction in body size in response to climate change in aquatic systems has been observed through long-term surveys and experimental data showing a significant increase in the proportion of small-sized species and young age classes and a decrease in size-at-age (Daufresne *et al.*, 2009). In the northern North Sea, due to species reorganisation (Beaugrand and Reid, 2012), a general decrease in the mean size of zooplankton over time has been observed. Smaller zooplankton species may have general implications for energy transfer efficiency to higher trophic levels, and for the sustainability of fisheries resources (Pitois and Fox, 2006)(Beaugrand and Kirby, 2010). In British waters, the lesser sandeel (*Ammodytes marinus*), which is a key link in the food web, shows declining recruitments since 2002 that are inversely correlated with temperature and is projected to further decline in the future with a warming climate (Heath *et al.*, 2012). In the Baltic Sea, marine-tolerant species will be disadvantaged and their distributions will partially contract; conversely, habitats of freshwater species will likely expand, Although some new species would be expected to immigrate because of an expected increase in sea temperature, only a few of these species would be able to successfully colonize the Baltic because of its low salinity (Mackenzie *et al.*, 2007).

Numerous studies confirm the amplification through fishing of the effects of climate change on population dynamics and consequently on fisheries (Planque *et al.*, 2010). Over the past decade, the cod stock has not been restored from its previous collapse (Mieszkowska *et al.*, 2009)(ICES, 2010). In the North Sea, the decline of cod during the 1980-2000 period results from the combined effects of overfishing and of an ecosystem regime shift due to climate change

(Beaugrand and Kirby, 2010). Analyses of fish species richness over 1997-2008 of North Sea and Celtic Seas did not detect the impact of fisheries (ter Hofstede *et al.*, 2010), as the steep decline in boreal species (Henderson, 2007) was compensated for by the arrival of southern (Lusitanian) species (Lenoir *et al.*, 2011). An observed weakening of the Iberian upwelling in the inner shelf has slowed down the introduction of nutrients, leading to changes in phytoplankton communities that favour the proliferation of harmful algal blooms, thereby reducing the permitted harvesting period for the mussel aquaculture industry.

The areal extent of some habitats that are suitable for aquaculture can be reduced by sea-level rise. In addition, ocean acidification may disrupt the early developmental stages of shellfish (Callaway *et al.*, 2012). Climate change may also reinforce parasitic diseases and impose severe risks for aquatic animal health. As water temperatures increase, a number of endemic diseases of both wild and farmed salmonid populations are *likely* to become more prevalent and difficult to control and threat levels associated with exotic pathogens may rise (Marcos-Lopez *et al.*, 2010). For oysters in France, toxic algae may be linked to both climate warming and direct anthropogenic stressors (Buestel *et al.*, 2009). With freshwater systems, summer heat waves boost the development of harmful cyanobacterial blooms (Johnk *et al.*, 2008). Therefore, current mitigation and water management strategies, which are largely based on nutrient input and hydrologic controls, must also accommodate the environmental effects of climate change (Paerl and Huisman, 2009)(Halpern *et al.*, 2012).

In the Iberian-Atlantic fishing grounds, the biomass and profits from sardine fishery will further decrease with greater intensity if the effects of global warming on the water temperature become more significant (Perez *et al.*, 2010)(Garza-Gil *et al.*, 2010). In the Bay of Biscay, a major part of the gross economic turnover associated with catches of fish species would potentially not be affected by long-term changes in climate (Floc'h *et al.*, 2008). In the Portuguese coast, a commercial opportunity for fisheries could arise since most the new potential species were marketable species and not many current species were lost under different climate scenarios (Vinagre *et al.*, 2011). Fishing fleets which presently target marine species (e.g. cod, herring, sprat, plaice, sole) in the Baltic may have to relocate to more marine areas or switch to other species which tolerate decreasing salinities. A temporary marine reserve policy in the Eastern Baltic could postpone the negative effects of climate change on fish stocks (Rockmann *et al.*, 2009).

Fishery management thresholds that trigger reductions in fishing quotas or fishery closures to conserve local populations (e.g. cod, salmon) will have to be reassessed as the ecological basis on which existing thresholds have been established changes, and new thresholds will have to be developed for immigrant species (Mackenzie *et al.*, 2007)(Beaugrand and Reid, 2012).

Integrative assessment help examine policy options (Miller *et al.*, 2010). Experimentation and innovation at local to regional levels is critical for a transition to ecosystem-based management (Osterblom *et al.*, 2010). Human social fishing systems dealing with high variability upwelling systems with rapidly reproducing fish species may have greater capacities to adjust to the additional stress of climate change than human social fishing systems focused on longer-lived and generally less variable species (Perry *et al.*, 2010; Perry *et al.*, 2011). However, the political and social implications of impacts on fisheries are hard to project. The climate-related northward movement of mackerel to Icelandic waters may create economic problems for fisheries in EU and policy debates (Arnason, 2012).

23.5. Implications of Climate Change for Health and Social Welfare

23.5.1. Human Population Health

Climate change is likely to have a range of health effects in Europe. Further studies since AR4 have confirmed the effects of heat on mortality and morbidity in European populations and particularly in older people and those with chronic disease (Åström *et al.*, 2011)(Kovats and Hajat, 2008). With respect to sub-regional vulnerability, populations in southern Europe appear to be most sensitive to hot weather (Åström *et al.*, 2013)(Baccini *et al.*, 2011)(Corobov *et al.*, 2011 (in press))(Iñiguez *et al.*, 2010; Tobías *et al.*, 2010), and also will experience the highest heat exposures (Iñiguez *et al.*, 2010; Tobías *et al.*, 2010) (Figure 23-2). However, elderly populations in central (Hertel *et al.*, 2009) and northern Europe (Rocklöv and Forsberg, 2010)(Armstrong *et al.*, 2011)(Varakina *et al.*,

2011) are also vulnerable to heat wave events. Adaptation measures to reduce heat health effects include heat wave plans (EEA-JRC-WHO, 2008) which have been shown to reduce heat-related mortality in Italy (Schifano *et al.*, 2012) and France. There is little information about how future changes in housing and infrastructure (e.g. retrofitting houses, installing cool rooms in residential homes) would reduce the regional or local burden of heat-related mortality. Most published risk assessments do not include consideration of adaptation (Huang *et al.*, 2011). Further work has been done to characterize heat stress as an occupational hazard (see chapter 11).

Climate change will increase the frequency and the intensity of major heat wave events (Figure 23-2), which are associated with significant acute impacts on mortality and morbiditiy (Robine *et al.*, 2008)(Solymosi *et al.*, 2010). Several studies have estimated the impact of climate scenarios on future heat-related mortality at the city level. A comparison of additional mortality in 15 cities (Baccini *et al.*, 2011) estimated highest attributable burdens in Budapest and Athens (A2 emissions scenario), with least impacts in Dublin, Zurich and Ljubljana by 2030. For most countries in Europe, the current burden of cold-related mortality is greater than the burden of heat mortality, although few studies have quantified benefits of climate warming in terms of the reduction of cold related mortality (Doyon *et al.*, 2008). A Europe-wide assessment, estimated that increase in heat-related mortality would only exceed the decrease in cold-related mortality at some point during the last third of the century assuming no adaptation, and an increased variance in daily temperature distributions (Ballester *et al.*, 2011).

Mortality and morbidity associated with flooding is becoming better understood although the surveillance of health effects of disasters remains inadequate. Additional mortality due to flooding has been estimated in the Netherlands due to sea level rise (Maaskant *et al.*, 2009); and in the UK for river flooding (Hames and Vardoulakis, 2012) but estimates of future mortality due to flooding are highly uncertain. There remains limited evidence regarding the long term mental health impacts of flood events (Paranjothy *et al.*, 2011)(Murray *et al.*, 2011).

Evidence about future risks from climate change with respect to infectious diseases is still limited (Semenza *et al.*, 2012)(Randolph and Rogers, 2010). There have been developments in mapping the current and potential future distribution of important vectors in Europe. The Asian tiger mosquito *Aedes albopictus*, is an important vector of dengue and other arboviruses, such as Chikungunya (Queyriaux *et al.*, 2008). The vector is currently present in many countries in southern and eastern Europe (ECDC, 2009). An assessment of the potential impact of climate change indicated limited potential for eastward expansion (ECDC, 2009)(Fisher *et al.*, 2011; Caminade *et al.*, 2012). A study in Italy projected the potential for northward shift of the vector's distribution in that country (Roiz *et al.*, 2011). For *Ae. Aegypti* (dengue vector that is not present in Europe), there are some areas that could potentially become suitable under climate change by 2050, including the Mediterranean areas of Spain, France and Italy as well as south-eastern Europe (ECDC, 2012). However, the risk of introduction of dengue remains very low because it would depend upon the upon the introduction and expansion of the *Ae. Aegypti* together with the absence of effective vector control measures (ECDC, 2012).

Visceral and cutaneous leishmaniasis are sandfly-borne diseases currently present in the Mediterranean region. A comprehensive review described that climate change is unlikely to affect the distribution of these infections in the near term (Ready, 2010). However, in the long term (15-20 years), there was potential for climate change to facilitate the expansion of either vectors or current parasites northwards . The risk of introduction of exotic Leishmania species was considered very low due to the low competence of current vectors (Fischer *et al.*, 2010a). The effect of climate warming on the risk of imported or locally-transmitted (autochthonous) malaria in Europe has been assessed in Spain (Sainz-Elipe *et al.*, 2010), France (Linard *et al.*, 2009) and the UK (Lindsay *et al.*, 2010). Disease re-emergence would depend upon many factors including: the introduction of a large population of infectious people or mosquitoes, high levels of people-vector contact, resulting from significant changes in land use, as well as climate change.

Since AR4 there have been several studies and reviews that have investigated the impact of climate change on food safety, at all stages from production to consumption (FAO, 2008; Jacxsens *et al.*, 2010; Popov Janevska *et al.*, 2010)(Miraglia *et al.*, 2009). The transmission of salmonellosis (a food pathogen) is sensitive to temperature but this sensivity has declined in recent years (Lake *et al.*, 2009) and the overall incidence of salmonellosis is declining in most European countries (ECDC, 2011). Climate change may also have affects on food consumption patterns (the reduction in consumption of animal products would benefit methane emissions reduction). Weather affects pre and

post harvest mycotoxin production but the implications of climate change are unclear. Cold regions may become liable to temperate-zone problems concerning contamination ochratoxin *A, patulin* and *Fusarium* toxins (Paterson and Lima, 2010). A control of the environment of storage facilities may avoid post-harvest problems but at additional cost (Paterson and Lima, 2010).

Other potential consequences concern marine biotoxins in seafood following production of phycotoxins by harmful algal blooms and the presence of pathogenic bacteria in foods following more frequent extreme weather conditions (Miraglia *et al.*, 2009). There is little evidence that climate change will affect human exposures to contaminants in the soil or water (e.g. persistent organic pollutants). Risk modelling is often developed for single exposure agents (e.g. a pesticide) with known routes of exposure. These are difficult to scale up to the population level. The multiple mechanisms by climate may affect transmission or contamination routes also makes this very complex (Boxall *et al.*, 2009).

Adaptation in the health sector has so far been largely limited to the development of heat health warning systems. A survey of national infectious disease experts in Europe identified several institutional changes that needed to be addressed to improve future responses to climate change risks: ongoing surveillance programs, collaboration with veterinary sector and management of animal disease outbreaks, national monitoring and control of climate-sensitive infectious diseases, health services during an infectious disease outbreak and diagnostic support during an epidemic (Semenza *et al.*, 2012).

23.5.2. Health Systems and Critical Infrastructure

Critical national infrastructure is defined as the assets (physical or electronic) that are vital to the continued delivery and integrity of the essential services upon which a country relies, the loss or compromise of which would lead to severe economic or social consequences or to loss of life. Extreme weather events, such as floods, heat waves and wild fires are known to damage critical infrastructure. The UK floods in 2007 leds to significant damage to power and water utilities, and damage to communications (including roads) responsible for 10% and 7% of the total costs, respectively (Chatterton *et al.*, 2010). Several countries have undertaken reviews of flood risks to hospitals, schools, water treatment/pumping stations. In 2007, a forest fire in Greece caused the closure of a major road and access to the international airport. Major storms in Sweden and Finland have led to loss of trees, with damage to the power distribution network, leading to electricity blackouts lasting weeks, as well as the paralysis of services such as rail transport and other public services that depend on grid electricity.

Health systems (hospitals, clinics) are also vulnerable to extreme events. The heat waves of 2003 and 2006 had adverse effects on patients and staff in hospitals from overheating of buildings. Evidence from France and Italy indicate that death rates in in-patients increased significantly during heat wave events (Ferron *et al.*, 2006; Stafoggia *et al.*, 2008). Further, higher temperatures have had serious implications for the delivery of health cares, as well drug storage and transport.

23.5.3. Social Impacts

There is little evidence regarding the implications of climate change for employment and/or livelihoods in Europe. However, the evidence so far (as reviewed in this chapter) indicates that there are likely to be changes to some industries (e.g. tourism, agriculture) that may lead to changes in employment opportunities by region and by sector in the longer term, particularly after mid-century.

The current burden for weather disasters is high (see above). Flooding can have long lasting effects of the affected populations (Schnitzler *et al.*, 2007). Households are often displaced while their homes are repaired. A flood event in the UK found that a significant proportion of persons were still displaced 12 months after the event (Whittle *et al.*, 2010). Little research has been carried out on the impact of extreme weather events such as heat waves and flooding on temporary or permanent displacement in Europe (EC, 2009a). Coastal erosion associated with sea level rise, storm surges and coastal flooding will require coastal retreat in some of Europe's low lying areas (Nicholls and

Cazenave, 2010)(Philippart *et al.*, 2011). Managed retreat is also an adaptation option in some coastal areas. Concerns have been raised about equality of access to adaptation within coastal populations at risk from climate change. For example, a study in the UK found that vulnerability to climate change in coastal communities is likely to be increased by social deprivation (Zsamboky *et al.*, 2011).

In the European region, the indigenous populations are present in Arctic regions are considered vulnerable to climate change impacts on livelihoods and food sources (Arctic Climate Impact Assessment, 2005) [12.3.4, 28.2.4]. Research has focussed on indigenous knowledge, impacts on traditional food sources and community responses/adaptation (Mustonen and Mustonen, 2011a; Mustonen and Mustonen, 2011b). However, these communities are also experiencing rapid social, economic and other non-climate-related environmental changes (such as oil and gas exploration) [see 28.2.4]. A study of European reindeer husbandary found that socio-economic factors were likely to be much more important than climate change for future sustainability (Rees *et al.*, 2008) [28.2.3.5].

23.5.4. Cultural Heritage and Landscapes

Climate change will affect the built environment that is culturally valued (Storm *et al.*, 2008) through extreme events and chronic damage to materials (Brimblecombe *et al.*, 2006; Brimblecombe and Grossi, 2010; Brimblecombe, 2010a; Brimblecombe, 2010b; Grossi *et al.*, 2011)(Sabbioni *et al.*, 2010). Cultural heritage is a non renewable resource and impacts from environmental changes are assessed over long timescales (Brimblecombe and Grossi, 2008)(Grossi *et al.*, 2008; Bonazza *et al.*, 2009a; Bonazza *et al.*, 2009b; Brimblecombe and Grossi, 2009; Brimblecombe and Grossi, 2010). Climate change may also affect indoor environments where cultural heritage is preserved (Lankester and Brimblecombe, 2010) as well as visitor behaviour at heritage sites (Grossi *et al.*, 2010).

Surface recession on marble and compact limestone will change in response to climate change. In the 2080s, Central Europe, Norway, the northern UK and Spain will experience surface recession ranging between 20 and 30 μm/y. Conversely, a decrease in surface recession of about 1-4 μm/y is projected for Southern Europe, reducing risk (Bonazza *et al.*, 2009a). Marble monuments located in the Mediterranean will continue to experience high levels of thermal stress (Bonazza *et al.*, 2009b). However, frost damage will reduce across Europe because of warming, except in Northern, and Alpine and permafrost areas (Iceland) (Grossi *et al.*, 2007; Sabbioni *et al.*, 2008). Damage to porous materials due to salt crystallisation may increase all over Europe (Benavente *et al.*, 2008; Grossi *et al.*, 2011). In Northern and Eastern Europe, wood structures will need additional protection against rainwater and some structures may need additional protection from high winds (Sabbioni *et al.*, 2010). AR4 concluded that then current flood defence schemes would not protect Venice from climate change. Venice now has a flood forecasting system, as well as the MOSE system of flood barriers (Keskitalo, 2010) but recent evidence suggests that climate change may lead to a decrease in the frequency of extreme storm surges (Troccoli *et al.*, 2011 (in press)).

Europe has many unique rural landscapes, which reflect the cultural heritage that has evolved from centuries of human intervention. Examples include, amongst others, the cork oak based Montado in Portugal, the Garrigue of southern France, Alpine meadows, grouse moors in the UK; machair in Scotland, peatlands in Ireland, and vineyards. Many, if not all, of these cultural landscapes are sensitive to climate change and even small changes in the climate could have significant impacts on their capacity to function as they have done in the past (Gifford *et al.*, 2011). Because of their cultural importance, many such landscapes are protected through rural development and environmental policies. Alpine meadows, for example, are culturally important within Europe, but although there is analysis of the economic (tourism, farming) and functional (water run-off, flooding, carbon sequestration) aspects of these landscapes there is very little understanding of the consequences for the cultural aspects of these areas and the societies who depend on them. Other European uplands, such as peat rich uplands in northern Europe have begun to consider landscape management as a means of adapting to the effects of climate change (e.g. the moors for the future partnership in the Peak District National Park, UK). For a discussion of the cultural implications of climate change for vineyards see Box 23-1.

_____ START BOX 23-1 HERE _____

Box 23-1. Implications of Climate Change Impacts for European Wine and Vineyards

There is a significant body of research on the impacts of climate change on wine production and the cultural landscapes embodied in vineyards (Metzger and Rounsevell, 2011) (White *et al.*, 2009). Wine production in Europe accounts for more than 60% of the global total (Goode, 2012) and makes an important contribution to cultural identity. It is also an exemplar of how climate change can affect not only the biophysical response of plants and the geographic distribution of wine grape varieties, but also consumer perceptions of wine that are associated with the cultural diversity of regional production. Taken together these effects make the European wine sector highly sensitive to climate change and one that is already taking climate adaptation seriously (Goode, 2012).

Apart from impacts on grapevine yield, higher temperatures are also expected to affect wine quality in some regions and grape varieties by changing the ratio between sugar and acids (Bock *et al.*, 2011)(Santos *et al.*, 2011)(Duchêne *et al.*, 2010). In western and central Europe, projected future changes could benefit wine quality, but might also demarcate new potential areas for viticulture (Malheiro *et al.*, 2010). Adaptation measures are already occurring in some vineyards (e.g. vine management, technological measures, production control and to a smaller extent relocation) (Battaglini *et al.*, 2009; Holland and Smit, 2010; Malheiro *et al.*, 2010; Duarte Alonso and O'Neill, 2011; Moriondo *et al.*, 2011; Santos *et al.*, 2011).

Whilst the distribution of grape suitability will change in response to climate change, relocation as an adaptation option is constrained by the concept of 'terroir', which combines the influence of a location's soils, climate and topography with the knowledge and traditions of wine producers, into a unique expression of landscape culture (Metzger and Rounsevell, 2011). Vineyards may be displaced geographically beyond their traditional boundaries, and in principle, wine producers could adapt to this problem by growing grape varieties that are more suited to warmer climates. Such technical solutions, however, do not account for the unique characteristics of wine production cultures and consumer perceptions of wine quality that strongly affect the prices paid for the best wines (Metzger and Rounsevell, 2011)(White *et al.*, 2009). It would become very difficult, for example, to produce fine wines from the cool-climate Pinot Noir grape within its traditional 'terroir' of Burgundy under many future climate scenarios, but consumers may not be willing to pay current day prices for red wines produced from other grape varieties (Metzger and Rounsevell, 2011). An additional barrier to adaptation is that wine is usually produced within rigid, regionally-specific, regulatory frameworks that often prescribe, amongst other things, what grapes can be grown where, e.g. the French AC or the Italian DOC and DOCG designations. Suggestions have been made to replace these rigid concepts of regional identity with a geographically flexible 'terroir' that ties a historical or constructed sense of culture to the wine maker and not to the region (White *et al.*, 2009).

_____ END BOX 23-1 HERE _____

23.6. Implications of Climate Change for the Protection of Environmental Quality and Biological Conservation

Terrestrial and freshwater ecosystems provide a number of vital services for people and society, such as biodiversity, food, fibre, water resources, carbon sequestration and recreation (Stoate *et al.*, 2009). Intensively managed ecosystems contribute mostly to vital provisioning services (e.g. agro-ecosystems provide food via crops and livestock, and forests provide wood). The condition of the majority of services shows either a degraded or mixed status across Europe with some exceptions, however, such as the recent enhancements in timber production and climate regulation in forests (Harrison *et al.*, 2010). Appropriate agricultural management practices are critical to realizing the benefits of ecosystem services (Power, 2010). Table 23-2 summarises the potential implications of climate change for ecosystem services in Europe.

[INSERT TABLE 23-2 HERE
Table 23-2: Impacts of climate change on ecosystem services.]

23.6.1. Air Quality

Climate change will have complex and local effects on pollution chemistry, transport, emissions and deposition. Outdoor air pollutants have adverse effects on human health, biodiversity, crop yields and cultural heritage. The main outcomes of concern are both the average (background) levels and peak events for tropospheric ozone, particulates, sulphur oxides (SO_x) and nitrogen oxides (NO_x). Future pollutant concentrations in Europe have been assessed using atmospheric chemistry models, principally for ozone (Forkel and Knoche, 2006; Forkel and Knoche, 2007). Reviews have concluded that GCM/CTM studies find that climate change per se (assuming no change in future emissions or other factors) is likely to increase summer tropospheric ozone levels (range 1–10 ppb) by 2050s in polluted areas (that is, where concentrations of precursor nitrogen oxides are higher) (AQEP, 2007; Jacob and Winner, 2009)[see also 21.4.1.3.2.]. The effect of future climate change alone on future concentrations of particulates, nitrogen oxides and volatile organic compounds is much more uncertain. Climate warming also affects natural emissions volatile organic compounds (VOCs) which are ozone precursors (Hartikainen *et al.*, 2012). One study has projected an increase in fire-related air pollution (O3 and PM10) in Southern Europe (Carvalho *et al.*, 2011).

Overall, the model studies are inconsistent regarding future projections of background level and exceedences. Recent evidence has shown adverse impacts on agriculture from even low concentrations of ozone, however, there is more consistent evidence now regarding the threshold for health (mortality) impacts of ozone. Therefore, it is unclear whether increases in background levels below health-related thresholds would be associated with an increased burden of ill health.

Some studies have attributed an observed increase in European ozone levels to observed warming (Meleux *et al.*, 2007), which appears to be driven by the increase in extreme heat events in 2003, 2006 and 2010 (Solberg *et al.*, 2008). Peak ozone events were observed during the major heat waves in Europe in multiple countries. Fire events have had an impact on local on air quality (Hodzic *et al.*, 2007; Liu *et al.*, 2009; Miranda *et al.*, 2009).

23.6.2. Soil Quality

The current cost of erosion, organic matter decline, salinisation, landslides and contamination is estimated to be EUR 38 billion annually for the EU25 (JRC-EEA, 2010), currently borne by society in the form of damage to infrastructures due to sediment runoff and landslides, treatment of water contaminated through the soil, disposal of sediments, depreciation of land around contaminated sites, increased food safety controls, and costs related to the ecosystem functions of soil (JRC-EEA, 2010).

Projections show significant reductions in summer soil moisture in the Mediterranean region, and increases in the north-eastern part of Europe (Calanca *et al.*, 2006). Soil water content will decline, saturation conditions will be increasingly rare and restricted to periods in winter and spring, and snow accumulation and melting will change, especially in the mid-mountain areas (García-Ruiz *et al.*, 2011). For the A2 emission scenario and a set of land use scenarios in Tuscany, even with a decline in precipitation volume until 2070, in some month higher erosion rates would occur due to higher rainfall erosivity (Marker *et al.*, 2008). However, a case study on cropped systems in Upper-Austria based on the A2 emission scenario (regional climate model HadRM3H) projects a small reduction in average soil losses under climate change in all tillage systems, however with high uncertainty (Scholz *et al.*, 2008). For a case study hillslope in Northern Ireland, with the A2 scenario downscaled GCMs generally result in erosion decreases, whereas large increases are projected when land use is changed from the current cover of grass to an arable crop which requires annual tillage (Mullan *et al.*, 2012). For scenario period 2071-2100, climate-change-induced changes in suspended sediment transport would increase for two Danish river catchments by 17 and 27% in alluvial and non-alluvial rivers, respectively, for steady-state land use scenarios (Thodsen, 2007; Thodsen *et al.*, 2008).

Under a business as usual land management scenario, taking into account the impacts of climate change on net primary productivity, a comparison of three soil models forced by climate scenarios derived from the HadCM3

climate model indicate a 10 % decline by 2070 in the organic carbon stocks of mineral soils for the croplands of European Russia and the Ukraine. Part of this decline could be mitigated by an environmentally sustainable management scenario (Smith, 2007). For EU25 plus Switzerland and Norway, projections under the A2 scenario for 1990 to 2080 of mineral soil organic carbon stocks in cropland and grassland soils show a small increase in soil carbon on a per area basis under future climate (+1 to +8%) for cropland and (+3 to +6%) for grassland (Smith J. *et al.*, 2005.). Similar values of soil organic C stock increase were simulated by a pasture model under the A1B climate scenario for two French grassland sites (Graux *et al.*, 2012). In these studies, soil carbon decline was faster in regions experiencing rapid warming combined with high soil moisture (e.g. Northern Europe), than in regions exposed to increased drought incidence (e.g. Southern Europe).Climate change may affect the distribution and degradation of organic pollutants, including persistent organic pollutants (Valle *et al.*, 2007).

Adaptive land-use management has a large potential for climate change response strategies concerning soil protection. In central Europe, compared to unsustainably high soil losses for conventional tillage, conservation tillage systems reduced modelled soil erosion rates under future climate scenarios by between 49 and 87% (Scholz *et al.*, 2008). Preserving upland vegetation cover is a win-win management strategy that will reduce erosion and loss of soil carbon, and protect a variety of services such as the continued delivery of a high quality water resource (House *et al.*, 2011)(McHugh, 2007). By absorbing up to twenty times its weight in water, increased soil organic matter can contribute to reduce risks of flooding. Maintaining water retention capacity is thus important, e.g. through adaptation measures (Post *et al.*, 2008). Soil conservation methods like zero tillage and conversion of arable to grasslands would maintain their protective effect on soil resources, independent of the climate scenario according to an up-scaling and modelling approach in SW-Germany that considered, however, in limited way climate-induced changes in the frequency and intensity of heavy rainstorms (Klik and Eitzinger, 2010).

23.6.3. Water Quality

Climate change may affect water quality in several ways, with implications for food production and forestry (see above 23.4.3), ecosystem functioning (Table 23-2), human and animal health, and compliance with European and national quality targets including those of the Water Framework Directive. Overall, because of the high heat capacity of water, shallow waters will witness a more rapid temperature increase and a parallel decrease in saturating oxygen concentrations. Since AR4, there is further evidence of adverse effects caused by short-term weather events: reductions in dissolved oxygen, algal blooms (Ulén and Weyhenmeyer, 2007)(Mooij *et al.*, 2008) during hot weather, and contamination of surface and coastal waters with sewage and/or chemicals (pesticides) after rainfall (Boxall *et al.*, 2009). A reduction in rainfall may lead to low flows which increase concentrations of biological and chemical contaminants. Reduced drainage can also enhance sedimentation in drainage systems and hence enhance particle-bound P-retention and reduce P-load to downstream higher order streams (Hellmann and Vermaat, 2012).

Future impacts of climate change on water quality include increased nutrient fluxes (Delpla *et al.*, 2011); impacts from increased water temperature and discharge reduction in the Seine river (Ducharne, 2008) and increased nutrient loads in Danish watersheds (Andersen *et al.*, 2006); increased summer temperature and drought leading to more favourable conditions for algal blooms and reduced dilution capacity of effluent in the Meuse river (van Vliet and Zwolsman, 2008). Several studies have investigated potential adverse impacts on nutrient flushing episodes and surface water quality in the UK (Whitehead *et al.*, 2006; Whitehead *et al.*, 2009)(Wilby *et al.*, 2006; Howden *et al.*, 2010; Macleod *et al.*, 2012)(See also AR5 WG2 Chapter 4.3.2.5). A modelling study on projected future water quality impacts for all EU27 countries indicated increased nutrient loadings in Northern Europe due to increased surface runoff in Southern Europe due to increased evapotranspiration (Jeppesen *et al.*, 2011).

23.6.4. Terrestrial and Freshwater Ecosystems

Habitats

Current and future climate changes have negative effects of habitat loss on species density and diversity (Mantyka-pringle *et al.*, 2012). Potential habitat shrinkage is occurring even when CO_2 physiological effects and water availability are taken into account (Rickebusch *et al.*, 2008).

Projected habitat loss is greater for species at higher elevations where, up to 36–55% of alpine plant species, 31–51% of subalpine plant species and 19–46% of montane plant species will lose more than 80% of their suitable habitat by 2070–2100 under B1and A1FI scenarios respectively (Engler *et al.*, 2011). Habitats of 150 alpine plant species on European Alps will suffer an average range size reduction of 44-50% and on average 40% of the range still occupied at the end of the century will be climatically unsuitable creating an extinction debt (Dullinger *et al.*, 2012). Suitable climatic conditions for Europe's breeding birds are projected to shift nearly 550 km northeast by the end of the century (Huntley *et al.*, 2007). In Great Britain mean altitude of the uplands is projected to increase for both B1 and A1FI scenarios by 2071–2100 with important implications on habitats, with in the eastern and southern regions low altitude areas (< 300 meters) being the most vulnerable (Clark *et al.*, 2010a).

In respect to the baseline distribution (1961-1990), British blanket peat and sub-arctic palsa mires, will reduce substantially suitable area by the period 2030-2049 under A1B and A2 emission scenarios (Fronzek *et al.*, 2006; Fronzek *et al.*, 2010; Gallego-Sala *et al.*, 2010; Clark *et al.*, 2010b; Fronzek *et al.*, 2011). Also changes in low flows result in reduction of fen and bog areas becoming marginal or unsuitable due to dryness (Harrison *et al.*, 2008). Across most of central, eastern and southern Europe, reduced hydro periods (the length of time and portion of year the wetland holds ponded water) and increased temperatures with parallel reduced oxygen in shallow waters and wetlands will have profound impacts on aquatic habitats and habitat connectivity in river networks may become increasingly fragmented (Elzinga *et al.*, 2007; Della Bella *et al.*, 2008; Blaustein *et al.*, 2010; Gómez-Rodríguez *et al.*, 2010; Hartel *et al.*, 2011; Morán-López *et al.*, 2012; Morán-López *et al.*, 2012).

Despite some local successes and increasing responses (including extent and biodiversity coverage of protected areas, sustainable forest management, policy responses to invasive alien species, and biodiversity-related aid), the rate of biodiversity loss does not appear to be slowing (Butchart *et al.*, 2010). Protected areas play a key role for conservation of biodiversity under climate change compared to unprotected areas, although by 2080, 58 ± 2.6% of the species would lose suitable climate in protected areas. Natura 2000 areas will be not effective or more impacted than unprotected areas, under A1FI, A2, B1, B2 scenarios (Araújo *et al.*, 2011). Similar concerns about effectiveness of protected areas are found for butterflies in Germany (Filz *et al.*, 2012). It has been highlighted the importance of taking into account the climate change projections on the selection of conservation areas (Araújo *et al.*, 2011; Filz *et al.*, 2012; Virkkala *et al.*, 2013).

Plant species

Observed changes in plant communities in European mountainous regions show a shift of species' ranges to higher altitudes due to climate warming (Pauli *et al.*, 2012) resulting in species richness increase in boreal-temperate mountain regions (+3.9 species on average) and decrease in Mediterranean mountain regions (–1.4 species) in 2001-2008 (Pauli *et al.*, 2012). Decline of the more cold adapted species and increase of the more warm-adapted has been observed, suggesting a progressive decline of cold mountain habitats and their biota (Gottfried *et al.*, 2012). The pollen season starts on average 10 days earlier than 50 years ago, an advance of 2.5 days per decade of spring and summer (Feehan *et al.*, 2009).

The most dramatic changes for plant species could occur in Northern Europe, where more than 35% of the species composition in 2100 could be new, and in Southern Europe, where up to 25% of the species now present would disappear (Alkemade *et al.*, 2011). Large range contractions up to 72% in 2080 due to climate change is projected for temperate tree species in European lowlands under A2 scenario (Casalegno et al., 2007). The increase in climatic aridity may compromise the survival of several populations of *Pinus sylvestris* in the Mediterranean basin

(Giuggiola *et al.*, 2010) while for the dominant Mediterranean tree species, Holm oak, a substantial range expansion is projected under A1B emissions scenario (Cheaib *et al.*, 2012). The scattered distributions of tree species, exacerbated in many cases by human activity, may make them more vulnerable to climate change because they probably have less ability to reproduce or adapt to shifting climate space than more widespread species (del Barrio *et al.*, 2006; Hemery *et al.*, 2010). By 2100, in southern Europe a great reduction in phylogenetic diversity of plant, bird and mammal assemblages will occur, and gains are expected in regions of high latitude or altitude for 2020, 2050 and 2080. However, losses will not be offset by gains and a trend towards homogenization across the continent will be observed (Thuiller *et al.*, 2011).

Animal species

Breeding seasons are lengthening, allowing extra generations of temperature-sensitive insects such as butterflies, dragonflies and pest species to be produced during the year (Feehan *et al.*, 2009). Climate change is altering the timing of spring migration of several bird species with species-specific response (Jonzén *et al.*, 2006; Rubolini *et al.*, 2007a; Rubolini *et al.*, 2007b). Climate change, together with land-use change, is likely to cause impacts on the abundance of birds of different breeding habitat, latitudinal distribution, and migratory behaviour, particularly on distance migrants (Jonzén *et al.*, 2006). Farmland birds and long-distance migrant species in Germany, Switzerland, and Austria declined whereas wetland bird species with southerly ranges increased in abundance (Lemoine *et al.*, 2007a; Lemoine *et al.*, 2007b). A northward shift in bird community composition has been observed (Devictor *et al.*, 2008) even if common species of European birds with the lowest thermal maxima showed the sharpest declines between 1980 and 2005(Jiguet *et al.*, 2010). Northern European species of butterflies appeared to be the most vulnerable in Europe (Heikkinen *et al.*, 2010). However, there is much species-to-species variation with individualistic response to climate change leading to the formation of new future non-analogous communities with species composition unlike any found today (Keith *et al.*, 2009).

Projections for 120 native terrestrial non-volant European mammals suggest that up to 5-9% are at risk extinction during the 21st century, while 32-46% or 70-78% may be severely threatened under A1 and B2 climatic scenarios (Levinsky *et al.*, 2007). Climate cooling would be more deleterious for the persistence of amphibian and reptile species than warming, even if decreases in the availability of water will be also problematic (Araújo *et al.*, 2006). Changes in temperature and precipitation will result in both changes in migratory species and adaptation of migratory activity (Schaefer *et al.*, 2008). Furthermore phenotype adaptation may allow species to persist *in situ*, conserving community composition (Schaefer *et al.*, 2008). However, populations not showing a phenological response to climate change fail to adjust to climate change and may decline (Molnar *et al.*, 2008) or causing ecological mismatches (Saino *et al.*, 2011). Climate change can affect trophic interactions, as co-occurring species do not necessarily react in a similar manner to global change (Schweiger *et al.*, 2012). Novel emergent ecosystems composed of new species assemblages arising from differential rates of range shifts of species can occur (Montoya and Raffaelli, 2010).

Invasive species

Climate change can exacerbate the threat posed by invasive species to biodiversity, both by direct and indirect effects such as changes to farm practices and introductions of exotic material and effects of other environment changes such as elevated CO_2 concentration and change in temperature and precipitation (West *et al.*, 2012). The western corn rootworm (maize pest in North America) has invaded Europe in recent years (Aragòn and Lobo, 2012). The 22.2% of the total number of mammal species in Europe are alien species (Genovesi *et al.*, 2012). Planktonic species typically encountered in tropical areas were observed in natural shallow lakes in the southwest of France during 2006 and 2007 possibly as a result of minimum temperatures increases registered over the last 30 years and could have played a key role in algal survival through winter (Cellamare *et al.*, 2010). The woody shrub Lantana (*Lantana camara* L.) that is highly invasive in many countries of the world may become climatically suitable under future climates in Europe (Taylor *et al.*, 2012). Climate scenarios of milder conditions for Atlantic Europe could lead to Giant rhubarb (*Gunnera tinctoria* (Molina) Mirbel.) and Brazilian giant rhubarb (*Gunnera manicata* L.) becoming more widely invasive (Skeffington and Hall, 2011). However the threat posed by invasive species to

biodiversity should be carefully considered as some studies demonstrate that fewer than 15% of species have more than 10% of their invaded distribution outside their native climatic niche (Petitpierre *et al.*, 2012).

23.6.5. Coastal and Marine Ecosystems

Climate change will affect Europe's coastal and marine ecosystems, altering the biodiversity, functional dynamics and ecosystem services of coastal wetlands, dunes, inter-tidal and subtidal habitats, offshore shelves, seamounts and currents (Halpern *et al.*, 2008) with changes in eutrophication, invasive species, species range shifts, changes in fish stocks and habitat loss (Doney *et al.*, 2011)(EEA, 2010e). The degree to which these changes will impact Europe's coasts and seas will vary temporally and spatially, requiring a range of adaptation strategies, targeting different policy scales, audiences and instruments (Philippart *et al.*, 2011)(Airoldi and Bec, 2007).

Europe's northern seas are experiencing greater increases in sea surface temperatures (SSTs) than the southern seas, with the Baltic, North and Black seas warming at 2-4 times the mean global rate (Philippart *et al.*, 2011)(Belkin, 2009). In the Baltic, decreased sea ice will lead to more exposed coastal areas and storms, changing the coastal geomorphology (BACC, 2008)(HELCOM, 2007). Warming SSTs will continue to influence biodiversity and drive changes in depth and latitudinal range for intertidal and sub-tidal marine communities, particularly in the North and Celtic seas (Hawkins *et al.*, 2011)(Sorte *et al.*, 2010)(Wethey *et al.*, 2011).

Warming is affecting food chains and varying rates of phenologies (Durant *et al.*, 2007), for example the reorganization in the timing and location of phytoplankton and zooplankton affects prey availability for North Sea cod (Beaugrand *et al.*, 2010)(Beaugrand and Kirby, 2010). Temperature-driven changes have affected the distribution of fisheries in all seas within the past 30 years, e.g., a decrease in the range of Atlantic cod in northern seas, while an increase in the abundance of coastal species such as the anchovy in subtropical regions. The range of the red mullet is increasing in extent from Norway to the northwest of Africa including the Mediterranean and Black Sea. In the Bay of Biscay, responses to climate change in 20 species of flatfish from 1987 to 2006 show that expanding species have a lower latitude range, than the declining species (Hermant *et al.*, 2010).

Warmer waters are also linked to invasive species which displace native species, further altering trophic dynamics, and productivity of coastal marine ecosystems, requiring a redefinition of invasive and native species (Molnar *et al.*, 2008)(Rahel and Olden, 2008). Changes in the semi-enclosed seas will be indicative of future conditions in other coastal-marine ecosystems (Lejeusne *et al.*, 2009). In the Mediterranean, a relatively high proportion of endemic species has been associated with the arrival of alien species at the rate of one introduction every 4 or 5 weeks in recent years (Streftaris *et al.*, 2005). While in the Mediterranean the endemic species distribution remained stable, most non-native species have spread northward by an average of 300 km since the 1980s, resulting in an area of spatial overlap with invasive species replacing natives by nearly 25% in 20 years (Beaugrand and Kirby, 2010).

Other future impacts of climate change in Europe's coastal-marine ecosystems include changes in circulation and nutrients in both open and semi-enclosed seas and coastal areas. Stratification of open seas will be primarily affected by the timing and strength of wind, whereas coastal areas will be vulnerable to storm surges (Philippart *et al.*, 2011). Freshwater input from melting of land-based ice has increased since the 1960s with a 10-30% increase from riverine input anticipated by 2100. Freshening of marine salinity is expected in upcoming decades throughout the North East Atlantic, with the Arctic freshening during the 21st century due to river run off, ice melt, and increases in the rate of the global water cycle. Drier summers along Biscay and Iberian coasts may lead to a decrease in nutrient input and enrichment with less runoff. Eutrophication will continue as a major issue in the Baltic (HELCOM, 2009). Yet, wetter winters and summers in the Arctic and North Sea may lead to higher nutrient input (OSPAR, 2010). Eutrophication and deteriorating marine water quality will lead to fewer fish, more jelly fish and more frequent algal blooms particularly in the semi-enclosed seas such as the Baltic (HELCOM, 2009). Before the end of 2100, surface waters of the Baltic Sea could inhibit calcium forming species, more so than the Black and Mediterranean Seas (CIESM, 2008).

Dune systems will be lost due to coastal erosion from combined storm surge and sea level rise in some places, requiring restoration and economic measures (Day *et al.*, 2008)(Ciscar *et al.*, 2011)(Magnan *et al.*, 2009). In the

North Sea, the Iberian coast, and Bay of Biscay, a combination of coastal erosion, infrastructure and sea defences may lead to narrower coastal zones ("coastal squeeze") (EEA, 2010e)(Jackson and McIlvenny, 2011)(OSPAR, 2010).

23.7. Cross-Sectoral Adaptation Decision-making and Risk Management

Most scientific studies on impacts and adaptation in Europe consider single sectors or outcomes, and have been discussed in previous sections of this chapter. For decision-making, more comprehensive and multi-sectoral approaches are required.

Since AR4, considerable progress has been made to advance planning and implementation of adaptation measures as well as the costing of adaptation (Section 23.7.6). Many European countries have now developed a series of national studies and strategies to address adaptation (see Box 23-2). The European Union has started a process of adaptation planning, focussing on information sharing (e.g. through the Climate Adaptation platform) as well as proposals for legislation following up on the White Paper on Adaptation (Dreyfus and Patt, 2012) and the EU Adaptation Strategy (to be published in March 2013).

_____ START BOX 23-2 HERE _____

Box 23-2. National and Local Adaptation Strategies

Several studies have evaluated national or local adaptation strategies with respect to implementation (Biesbroek *et al.*, 2010). Many adaptation strategies were found to be agendas for further research, awareness raising and/or coordination and communication for implementation (e.g. (Pfenniger *et al.*, 2010)(Dumollard and Leseur, 2011). Actual implementation often relates to natural hazard prevention, environmental protection, coastal zone and water resources management. The implementation of planned adaptation at the national level was attributed to political will and good financial and information capacity (Westerhoff *et al.*, 2011)(Biesbroek *et al.*, 2010)(Swart *et al.*, 2009) found for seven national adaptation strategies that while there is a high political commitment to adaptation planning and implementation, evaluation of the strategies and actual implementation is yet to be defined. One of the earliest national adaptation strategies (Finland) has been evaluated, in order to compare identified adaptation measures with those launched in different sectors. It has found that while good progress has been made on research and identification of options, few measures have been implemented except in the water resources sector (Ministry of Agriculture and Forestry, 2009).

At the local government level, adaptation plans are being developed in several cities, including London (GLA, 2010), Madrid, Manchester, Copenhagen, Helsinki, and Rotterdam. Adaptation in general is a low priority for many European cities, and many plans do not have adaptation priority as the main focus (Carter, 2011). Many studies are covering sectors sensitive to climate variability, as well as sectors that are currently under pressure from socioeconomic development. A recent assessment found a lack cross-sector impact and adaptation linkages as an important weakness in the city plans (Hunt and Watkiss, 2011). Flexibility in adaptation decision making needs to be maintained (Hallegatte *et al.*, 2008)(Biesbroek *et al.*, 2010).

_____ END BOX 23-2 HERE _____

23.7.1. Coastal Zone Management

Coastal zone management and coastal protection plans that integrate adaptation concerns are now implemented. Underlying scientific studies increasingly assess effectiveness and costs of options (Hilpert *et al.*, 2007)(Kabat *et al.*, 2009)(Dawson *et al.*, 2011) (see also section 23.7.6). Measures to mainstream adaptation into sectoral policies need to provide early response measures for floods and coastal erosion, and ensure that climate change considerations are incorporated into marine strategies with mechanisms for regular updating (OSPAR, 2010; UNEP, 2010).

In the Dutch plan for coastal protection (Delta Committee, 2008), adaptation to climate change, increasing river runoff and sea level rise plays a prominent role. It also includes synergies with nature conservation, increasing storage for water supply (Kabat *et al.*, 2009), and links to urban renovation. Its cost estimates are included in Section 23.7.6. While that plan mostly relies on large scale measures, new approaches such as small-scale containment of flood risks through increasing compartimentalisation are also studied (Klijn *et al.*, 2009). The UK government has developed extensive adaptation plans (TE2100) to adjust and improve flood defences for the protection the Thames Estuary and London from future storm surges and flooding (Environmental Agency, 2009). An elaborate analysis has provided insight in the pathways for different adaptation options and decisions that depend on the eventual sea-level rise.

23.7.2. Integrated Water Resource Management

Water resources management has experienced a general shift from "hard" to "soft" measures which allow more flexible responses to environmental change (Pahl-Wostl, 2007). Integrated water resource management explicitly includes the consideration of environmental and social impacts (Wiering and Arts, 2006). Climate change has been incorporated into water resources planning in England and Wales (Arnell, 2011)(Charlton and Arnell, 2011)(Wade *et al.*, 2012) and in the Netherlands (de Graaff *et al.*, 2009). The robustness of adaptation strategies for water management in Europe has been tested in England (Dessai and Hulme, 2007) and Denmark (Haasnoot *et al.*, 2012; Refsgaard *et al.*, 2013). Other studies have emphasised the search for robust pathways, for instance in the Netherlands (Kwadijk *et al.*, 2010; Haasnoot *et al.*, 2012). Public participation has also increased in decision making, e.g. river basin management planning (Huntjens *et al.*, 2010), flood defence plans (e.g. TE2100), and drought contingency plans (Iglesias *et al.*, 2007). Guidance has been developed on the inclusion of adaptation in water management (UNECE, 2009) and river basin management plans (EC, 2009b). A study of policymakers, including local basin managers, identified several important barriers to the implementation of adaptation strategies in the water sector (Brouwer *et al.*, 2013).

23.7.3. Disaster Risk Reduction and Risk Management

A series of approaches to disaster risk management are employed in Europe, in response to national and European policy developments to assess and reduce natural hazard risks. New developments since the AR4 include assessment and protection efforts in accordance with the EU Floods Directive (European Parliament and Council, 2007), the mapping of flood risks, as well as other proposals to reduce impacts from natural hazards and improve civil protection response. But most countries have so far focussed on hazard assessment and less on analysis of possible impacts (de Moel *et al.*, 2009). The effectiveness has been assessed of flood protection (Bouwer *et al.*, 2010) and also non-structural or household level measures to reduce losses from river flooding (Botzen *et al.*, 2010a) (Dawson *et al.*, 2011). Some studies show that current plans may be insufficient to cope with increasing risks from climate change, as shown for instance for the Rhine river basin (Te Linde *et al.*, 2010a; Te Linde *et al.*, 2010b).

Other options that are being explored are the reduction of consequences, responsive measures, as well as other options for insuring and transferring losses (see SREX report; and Section 23.3.7). The Netherlands carried out a large-scale analysis and simulation exercise to study the possible emergency and evacuation response for a worst-case flood event (ten Brinke *et al.*, 2010). Increasing attention is also being paid in Europe to non-government actions that can reduce possible impacts from extreme events. Terpstra and Gutteling (2008) found through a survey that individual citizens are willing to assume some responsibility for managing flood risk, and they are willing to contribute to preparations in order to reduce impacts. Survey evidence is available for Germany and the Netherlands that, under certain conditions, individuals can be encouraged to adopt loss prevention measures (Thieken *et al.*, 2006)(Botzen *et al.*, 2009). Small businesses can reduce risks when informed about possibilities immediately after an event (Wedawatta and Ingirige, 2012).

23.7.4. Land Use Planning

Through effects on land use and the spatial configurations of cities, spatial planning policies can build resilience to the impacts of climate change (Bulkeley, 2010). However, the integration of adaptation considerations into spatial planning is limited to a general level of policy formulation that lacks concrete instruments and measures for implementation in practice (Mickwitz *et al.*, 2009)(Swart *et al.*, 2009). There is evidence to suggest a systematic failure of planning policy to account for climate and other environmental changes (Branquart *et al.*, 2008) and a lack of institutional frameworks in support of adaptation is a major barrier to the governance of adaptation through spatial planning (ESPACE, 2007). In many countries, climate change adaptation is treated primarily as a water management or flooding issue, which omits other important aspects of adaptation leading to partial solutions (Mickwitz *et al.*, 2009)(Wilson, 2006)(Van Nieuwaal *et al.*, 2009). For example, in the UK, surveys of local authorities found an overall increase in the area covered by buildings in areas at risk from flooding compared with change across the locality as a whole (2001-2011) (ARUP, 2011).

City governance is also dominated by the issues of climate mitigation and energy consumption rather than assisting cities in adapting to climate change through spatial planning (Bulkeley, 2010). Some cities, e.g. Rotterdam, have started to create climate adaptation plans and this process tends to be driven by the strong political leadership of mayors (Sanchez-Rodriguez, 2009). The Helsinki Metropolitan Area's Climate Change Adaptation Strategy (HSY, 2010) is a regional approach focusing on the built urban environment in the cities of Helsinki, Espoo, Vantaa and Kauniainen, and their surroundings with approximately 1.2 million inhabitants (ca. 20% of the Finnish population). It includes approaches for dealing with increasing heat waves, more drought periods, milder winters, increasing (winter) precipitation, heavy rainfall events, river floods, storm surges, drainage water floods and sea level rise.

Green infrastructure provides climate adaptation and mitigation benefits as well as offering a range of other benefits to urban areas, including health improvements, better amenity value, inward investment, increasing property values and the reduction of noise and air pollution. Thus green infrastructure is an attractive climate adaptation strategy since it simultaneously contributes to the sustainable development of urban areas (Gill *et al.*, 2007; James *et al.*, 2009). Urban green space and green roofs can moderate temperature and decrease surface rainwater run-off (Gill *et al.*, 2007). Despite the benefits however of urban green space, conflict can occur between the use of land for green space and building developments (Wilson, 2008).

European policies for biodiversity (e.g. the European Biodiversity Strategy (EC, 2011)) look to spatial planning to help protect and safeguard internationally and nationally designated sites, networks and species, as well as locally valued sites in urban and non-urban areas, and to create new opportunities for biodiversity through the development process (Wilson, 2008). Conservation planning in response to climate change impacts on species will involve several strategies that better manage isolated habitats, increase colonisation capacity of new climate zones and optimise conservation networks to establish climate refugia (Vos *et al.*, 2008).

23.7.5. Rural Development

Rural development is one of the key policy areas for Europe, yet there is little or no discussion about the role of climate change in affecting future rural development. The EU White Paper on adapting to climate change (EC, 2009a) encourages Member States to embed climate change adaptation into the three strands of rural development aimed at improving competitiveness, the environment, and the quality of life in rural areas. It appears however that little progress has been made in achieving these objectives.

The EUs Leader programme was designed to help rural actors improve the long-term potential of their local areas by encouraging the implementation of sustainable development strategies. A significant number of Leader projects address climate change adaptation, but only as a secondary or in many cases a non-intentional by-product of the primary rural development goals. The World Bank's community adaptation project has seen a preponderance of proposals from rural areas in Eastern Europe and Central Asia (Heltberg *et al.*, 2012) suggesting that adaptation based development needs in Eastern Europe are currently not being met by policy.

23.7.6. Economic Assessments of Adaptation

Compared to studies assessed in AR4 (AR4 WG2, Chapter 17.2.3), costs estimates for Europe are increasingly derived from bottom-up and sector-specific studies, aimed at costing response measures (Watkiss and Hunt, 2010), in addition to the economy-wide assessments (Aaheim *et al.*, 2012). The evidence base, however, is still fragmented and incomplete. The coverage of adaptation costs and benefit estimates is dominated by structural (physical) protection measures, where effectiveness and cost components can be more easily identified. For energy, agriculture, infrastructure there is medium coverage of cost and benefit categories. For other sectors, such as health and welfare, estimates are generally lacking. Table 23-3 summarises some of the more comprehensive cost estimates for Europe for sectors at regional and national level. It is stressed that the costing studies use a range of methods and metrics and relate to different time periods and sectors, which renders robust comparison difficult. As an example, the large differences in the cost estimates between coastal and river protection in Europe and the Netherlands (Table 23-3) are due to the objectives for adaptation and the large differences in the level of acceptable risk: e.g. Rojas *et al.* (2012) assess a 1 in 100 year level of protection for Europe, while the Netherlands has set standards up to 1 in 4,000 and 10,000 year level return periods. More detailed treatment of the economics of adaptation is provided in AR5 WG2 Chapter 17.

[INSERT TABLE 23-3 HERE
Table 23-3: Adaptation cost estimates for European countries.]

23.8. Co-Benefits and Unintended Consequences of Adaptation and Mitigation

The impacts of and responses to climate change cannot be considered in isolation. Scientific evidence for decision making is more useful if impacts are considered in the context of impacts on other sectors and in relation to adaptation, mitigation and other important policies (Mokrech *et al.*, 2012). The benefits of adaptation and mitigation policies can be felt in the near term and in the local population, although benefits relating to greenhouse gas emissions reduction may not be apparent until the longer term (Zylicz, 2010). The benefits of adaptation measures are often assessed using conventional economic analyses, some of which include non-markets costs and benefits (externalities)(Watkiss and Hunt, 2010). This section will describe policies, strategies and measures where there is good evidence regarding mitigation/adaptation costs and benefits. Few studies have quantified directly the trade-offs/synergies for a given policy.

23.8.1. Production and Infrastructure

Mitigation policy (decarbonisation strategies) is likely to have important implications for dwellings across Europe. The unintended consequences of mitigation in the housing sector include: changes to household energy prices and adverse effects from decreased ventilation in dwellings (Davies and Oreszczyn, 2012). Energy efficiency interventions may effect indoor summer temperatures, some acting to reduce temperatures and others acting to increase temperatures (Mavrogianni *et al.*, 2012) and on the concentration of indoor pollutants (Shrubsole *et al.*, 2012). The effect of mitigation measures such as electrical equipment improvements is more complicated; a simulation of a typical UK office indicated that the reduction of internal heat gains as a result of more energy efficient PCs, low energy LCD display technology, improved power management and energy efficient lighting can reduce the peak cooling requirement by up to 27% even under a 2030 warming climate, i.e. +1 ^{o}C compared to 2005 (Jenkins *et al.*, 2008; Jenkins, 2009). However, as space heating requirements would also increase following these interventions, the location, type and dominant energy use of the building will determine its overall energy gain or loss to maintain comfort levels.

Adaptation measures such as the use of cooling devices will probably increase a building's energy consumption if no other mitigation measures are applied. There have been few studies on the future demand for energy-intensive space cooling in Europe, although the majority of energy modelling studies assume increased uptake driven by

climate and non-climate factors (see chapter 10). The potential for cooling dwellings without increased energy consumption, and with health benefits is large (Wilkinson *et al.*, 2009).

When looking at the broader context of urban infrastructures, despite existing efforts to include both adaptation, and mitigation into sustainable development strategies at city level (e.g. Hague, Rotterdam, Hamburg, Madrid, London, Manchester), priority on adaptation still remains low (Carter, 2011). There is potential to develop strategies that can address both mitigation and adaptation solutions, as well as have health and environmental benefits (Milner *et al.*, 2012). In energy supply, the adverse effect of climate change on water resources in some coastal regions in southern Europe may further enhance the development of desalination plants as an adaptation measure, consequently increasing energy consumption and thus greenhouse gases emissions.

In tourism, adaptation and mitigation may be antagonistic, as in the case of artificial snowmaking in European skiing resorts which requires significant amounts of energy and water (OECD, 2007; Rixen *et al.*, 2011) and the case of desalination for potable water production which also requires energy. However, depending on the location and size of the resort, implications are expected to differ and thus need to be investigated on a case-by-case basis. A similar relationship between adaptation and mitigation may hold for tourist settlements in southern Europe, where expected temperature increases during the summer may require increased cooling in order to maintain tourist comfort and thus increase greenhouse gas emissions and operating costs. Furthermore, a change of tourist flows as a result of tourists adapting to climate change may affect transport emissions, while mitigation in transport could also lead to a change in transport prices and thus possibly affect tourist flows.

23.8.2. Agriculture, Forestry, and Bioenergy

Agriculture and forestry face two challenges under climate change, both to reduce emissions and to adapt to a changing and more variable climate (Smith and Olesen, 2010)(Lavalle *et al.*, 2009). The agriculture sector contributes to about 10% of the total anthropogenic greenhouse gas (GHG) emissions in the European Union (EEA, 2010b). Estimates of European carbon dioxide, methane and nitrous oxide fluxes between 2000 and 2005 suggest that methane emissions from livestock and nitrous oxide emissions from agriculture are fully compensated for by the carbon dioxide sink provided by forests and by grassland soils (Schulze *et al.*, 2010). However, projections suggest a significant decline of the forest carbon sink until 2030 in the baseline scenario of about 25–40 compared to 2010 estimate. Including additional bioenergy targets of EU member states has an effect on the development of this sink, which is not accounted in the EU emission reduction target (Bottcher *et al.*, 2012).

Many agricultural practices can potentially mitigate GHG emissions, the most prominent of which are improved cropland and grazing land management and restoration of degraded lands and cultivated organic soils (Smith and Olesen, 2010). Reducing excesses of nitrogen fertilization and substitution of mineral N fertilizers by biological N fixation, as well as improved nutrition of domestic ruminants to reduce methane from enteric fermentation and improved manure management can play a significant role. Lower, but still significant mitigation potential is provided by water and rice management and agro-forestry (Smith and Olesen, 2010). Preserving European soil and forest carbon stocks through careful land use planning and agricultural and forestry management will be required to avoid positive feedbacks on global warming (Schulze *et al.*, 2010) especially during heat and drought extreme events (Ciais *et al.*, 2005). Synergies and trade-offs between mitigation and adaptation need to be incorporated into economic analyses of the mitigation costs (Smith and Olesen, 2010).

In arable production systems, adapting by increasing the resilience to temperature and rainfall variability would have positive impacts on mitigation by reducing soil erosion, as well as soil organic carbon and nitrogen losses. Improving soil water holding capacity through adding crop residues and manure to arable soils or by adding diversity to the crop rotations may contribute both to adaptation and to mitigation (Smith and Olesen, 2010). In contrast, increased irrigation under climate change will increase energy use and may reduce water availability for hydro-power (reduced mitigation potential) (Wreford *et al.*, 2010). Nevertheless, irrigation may enhance soil carbon sequestration in arable systems (Rosenzweig *et al.*, 2008)(Rosenzweig and Tubiello, 2007). In livestock intensive systems, warmer conditions in the coming decades might trigger the implementation of enhanced cooling and ventilation systems (Rosenzweig and Tubiello, 2007), thereby increasing energy use and associated GHG emissions.

In grass-based livestock systems, adaptation by adjusting the mean annual animal stocking density to the herbage growth potential (Fitzgerald *et al.*, 2010)(Graux *et al.*, 2012) is *likely* to create a positive feedback on GHG emissions per unit area (Soussana and Luscher, 2007; Soussana *et al.*, 2010).

Mitigation measures may encourage the production of energy crops, or forestry, in areas that are vulnerable to extreme events (e.g. fires, storms, droughts) or with high water demand, therefore increasing demands on adaptation (Wreford *et al.*, 2010). Conversely, the potential expansion of agriculture at high latitudes may release large amounts of carbon and nitrogen from organic soils, thereby leading to increased demands on mitigation (Rosenzweig and Tubiello, 2007). Available land for bioenergy crops is foremost to be found in Eastern Europe (De Wit *et al.*, 2011). The total available land in Europe (EU27 and Ukraine) for bioenergy crop production could amount to 900 000 km^2 by 2030. Agricultural residues of food and feed crops may provide an additional source for biofuel production. Up to 246 Mt agricultural residues could be available for biofuel production (assuming up to 50% of crop residues can be used without risks for agricultural sustainability) which is comparable to feedstock plantations of 15-20 million hectares (Fischer *et al.*, 2010b). Bioenergy crops could occupy significant areas of rural land within 20 years in the UK (Haughton *et al.*, 2009).

23.8.3. Social and Health Impacts

Significant research has been undertaken since AR4 on the health co-benefits of mitigation policies (see WGIII chapters on Housing, Transport and Energy, and WGII chapter 11). Several assessment have quantified benefits in terms of lives saved by reducing particulate air pollution, and trying to coherent policy objectives for emissions reductions in local and global pollution. Policies that improve health from changes in transport and energy can be said to have a general benefit to population health and resilience (Haines *et al.*, 2009a; Haines *et al.*, 2009b).

Changes to housing and energy policies also have indirect implications for human health. Researches on the benefits of various housing options (including retrofitting) have been intensively addressed in the context of low energy, healthy and sustainable housing (see WGIII).

23.8.4. Environmental Quality and Biological Conservation

Marine protected areas (MPAs) provide place-based management of marine ecosystems through various degrees and types of protective actions. MPA networks are generally accepted as an improvement over individual MPAs to address multiple threats to the marine environment. While MPA networks are considered a potentially effective management approach for conserving marine biodiversity, they should be established in conjunction with other management strategies, such as fisheries regulations and reductions of nutrients and other forms of land-based pollution. Information about interactions between climate change and more "traditional" stressors is limited. MPA managers are faced with high levels of uncertainty about likely outcomes of management actions because climate change impacts have strong interactions with existing stressors, such as land-based sources of pollution, overfishing and destructive fishing practices, invasive species, and diseases. Management options include ameliorating existing stressors, protecting potentially resilient areas, developing networks of MPAs, and integrating climate change into MPA planning, management, and evaluation (Keller *et al.*, 2009). Results in a Mediterranean coastal zone demonstrate that the declaration of a marine reserve alone does not guarantee the sustainability of marine resources and habitats but should be accompanied with an integrated coastal management plan (Lloret and Riera, 2008).

Figure 23-8 illustrates the consequences of the relationships between mitigation and adaptation options and biodiversity (Paterson and Lima, 2010)(Paterson *et al.*, 2009). There are very few management approaches that are win-win-win in terms of mitigation, adaptation and biodiversity and some of these (e.g. forest pest control) have limited implications in terms of adapting to climate change. Other adaptation options, such as desalinisation, sea defences and flood control infrastructure have decidedly negative effects on both mitigation and biodiversity. However, some approaches, such as forest conservation and urban green space (see earlier) have multiple benefits and potentially significant effects.

[INSERT FIGURE 23-8 HERE
Figure 23-8: Adaptation and mitigation options and their effects on biodiversity. Based on Paterson et al., 2009.]

There has been relatively little research about the impacts of future land use demand for bioenergy production, food production and urbanisation on nature conservation.

23.9. Intra-Regional and Inter-Regional Issues

Climate change will have a range of impacts in different European sub-regions. The adaptive capacity of populations is likely to vary significantly within Europe. Adaptive capacity indicators have been developed based on future changes in socio-economic indicators and projections (Metzger *et al.*, 2008; Lung *et al.*, 2012)(Acosta-Michlik *et al.*, 2013; Greiving et al., ESPON). These studies concluded that the Nordic countries have higher adaptive capacity than most of the Southern European countries, with countries around the Mediterranean having a lower capacity than the countries around the Baltic Sea region. Eastern European countries have, in general, lower adaptive capacity than Western or Northern European countries.

23.9.1. Implications of Climate Change for Distribution of Economic Activity within Europe

Table 23-4 summarises the future impacts by each sub-regions. A key finding is that all regions are vulnerable to some impacts from climate change but that these impacts differ significantly in type between the sub-regions. Impacts in neighbouring regions (inter-regional) may redistribute economic activities across the European landscape. The sectors most likely to be affected by climate change, and therefore with implications for economic activity and population movement (changes in employment opportunities) include: tourism, agriculture, and forestry.

[INSERT TABLE 23-4 HERE
Table 23-4: Assessment of future climate change impacts by sub-region and sector (by 2050, medium emissions).]

Economic assessments of impacts across sectors and across Europe indicate large variations across subregions (Ciscar *et al.*, 2011). Annual loss in household welfare in the EU27 resulting from the four market impacts (agriculture, river floods, coastal areas, and tourism) would range between 0.2-1% by 2080s (Ciscar *et al.*, 2011). Northern Europe is the only region project to have net economic benefits in these sectors, driven mainly by the positive effects on agriculture. Coastal systems, agriculture, and river flooding are the most important of the four market impacts assessed.

Impacts of climate change losses on local economies are more serious in a large-scale scenario when neighbouring provinces are also affected by drought and heat wave events. This is due to the supply-side induced price increase leading to some passing on of disaster costs to consumers (Mechler *et al.*, 2010). Growing temperatures across Europe could affect the relative quality of life in different regions which in turn could change the intensity and direction of internal migration flows (as one factor in individuals migration decision making strategy could be temperature) (Kerr and Kerr, 2011).

Climate change may also affect policies regulating agriculture and fisheries across European sub-regions. The Less Favoured Areas (LFA) scheme is a broad European policy mechanism for improving the viability of agriculture in areas with natural handicaps. Land suitability for agricultural production is classified based on climate, soil, and terrain criteria. By 2030, part of Northern Europe would leave areas with climate constraint zone basically because of mean annual temperature increase, while part of central and South Europe would enter these areas as a result of increased aridity (Donatelli *et al.*, 2012). The European Union Common Fisheries Policy is also questioned by changes in the distribution of fish stocks which could affect total allowable catches and their allocations to member states (Arnason, 2012).

23.9.2. Climate Change Impacts Outside Europe and Inter-Regional Implications

In an increasingly globalised world, impacts of climate change in other countries are likely to affect countries within the Europe region. Further, the region is very closely linked to its near neighbours. Countries around the Mediterranean share similar ecologies and therefore some vulnerability (see Box 23-3; see also Chapter 22).

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Box 23-3. Climate Change Impacts in the Mediterranean

The Mediterranean area (which encompasses two IPCC regions: Europe and Africa) is particularly vulnerable to climate change. Mediterranean ecosystems have been strongly modified from millennia of human occupation and use. At present, habitat loss and degradation, as well as extraction, pollution, eutrophication and the introduction of alien species, and recently climate change, are the most important threats that affect the greatest number of taxonomic groups occurring in the Mediterranean Sea (Costello *et al.*, 2010; Coll *et al.*, 2012). Areas with high marine biodiversity in the Mediterranean Sea are mainly located along the central and north shores, with lower values in the south-eastern regions (Coll *et al.*, 2012). Areas of potential high cumulative threats are widespread in both the western and eastern basins, with fewer areas located in the south-eastern region. The interaction between areas of high biodiversity and threats for invertebrates, fishes and large animals in general (including large fishes, marine mammals, marine turtles and seabirds) is concentrated in the coastal areas of Spain, Gulf of Lions, north-eastern Ligurian Sea, Adriatic Sea, Aegean Sea, south-eastern Turkey and regions surrounding the Nile Delta and north-west African coasts. Socio-economic factors are likely to increase competition for water and land degradation in the region (Hoff, 2012). Agricultural production will be exposed to increased heat waves and droughts with a potential for negative impacts that will be exacerbated by the competition for water with other sectors (see 23.4.3). It is uncertain if tourism flows will decline in the Mediterranean countries (see 23.3.6). Climate change is expected to trigger a more severe fire regime and more difficult conditions for ecosystem restoration after fire (Anav *et al.*, 2010)(Moriondo *et al.*, 2006)(Duguy *et al.*, 2012).

_____ END BOX 23-3 HERE _____

The high volume of international travel increases Europe's vulnerability to invasive species, including the vectors of human and animal infectious diseases. The transport of animals and animal products has faciliated the spread of animal diseases (Conraths and Mettenleiter, 2011). Important "exotic" vectors that have become established in Europe include the vector *Aedes albopictus* (Becker, 2009) (see Section 23.5.1 above) and a novel vector of blue tongue virus (see 23.4.3).

Another inter-regional implication concerns the changes in the location of commercial fish stocks shared with non-member states. Such changes may render existing international agreements regarding the sharing of yield from these stocks obsolete giving rise to international disputes (Arnason, 2012). For instance, in the North Atlantic, the mackerel stock has recently been extending beyond the EU jurisdiction into the Exclusive Economic Zones of Iceland and the Faroe Islands (Astthorsson *et al.*, 2012).

There are few robust studies of future climate-change related population movement either within or into the European region. Although several studies have proposed a role of climate change to increase migration pressures in low and middle income countries in the future, there is little robust information regarding the role of climate, environmental resource depletion and weather disasters in future inter-continental population movements (Kolmannskog and Myrstad, 2009; Kolmannskog, 2010). The effect of climate change on external migration flows into Europe is highly uncertain (see chapter 12.4.1 for a more complete discussion). Modelling future migration patterns is complex and so far no robust approaches have been developed.

23.10. Synthesis of Key Findings

23.10.1. Key Vulnerabilities

Context to key vulnerabilities:

- Many key vulnerabilities are already well known since the AR4, but some new vulnerabilities are emerging in AR5
- The policy/governance context in Europe is extremely important in determining key vulnerabilities (either mitigating or exacerbating vulnerability) since Europe is a highly regulated region.
- Vulnerability will be strongly affected by changes in the non-climate drivers of change (e.g. economic, social, governance, technological drivers), and for many sectors this will be more important than climate change.
- Future vulnerability will also be strongly affected by cross-sectoral (indirect) interactions, e.g. flooding-ecosystems, agriculture-species, agriculture-cultural landscapes, and so on.
- Extreme events (heat waves and droughts) have had significant impacts on populations as well impacts on multiple economic sectors, and resilience to future heat waves has only been addressed within some sectors.

Already known vulnerabilities (AR4) confirmed in AR5:

- More heat-related deaths and health issues due to an increase in heat waves, particularly in Southern Europe.
- Increases in pests and diseases, with implications for plant, animal and human health.
- Increase in energy demand in summer and reduction in winter.
- The key vulnerability for forests arises from species decline and increase in wild fires and pests and diseases
- Alpine species in particular are vulnerable to climate change (due to a lack of migration potential)
- The ski tourism sector is highly vulnerable to reductions in snow cover arising from warming
- Decrease of the hydropower potential in southern regions and increase in northern regions
- Reduced production in some thermal power plants due to cooling water shortages
- Coastal zones (including both natural environments and settlements) are highly vulnerable to sea level rise
- Settlements across Europe are vulnerable to flooding.

Emerging vulnerabilities:

- Arable crop yields. There is new evidence to suggest that crop yields and production may be more vulnerable as a result of increasing climate variability. This will limit the potential poleward expansion of agricultural production. Limits to genetic progress to adapt are increasingly reported.
- Water will be less available and will be in increased demand and degraded state of water tables. There is the potential for increased competition between the agricultural, domestic, power sector, industrial and natural (animal and plant species) users of water. Future problems are likely to occur unless integrated water management is widely adopted.
- Increased summer energy demand, especially in southern Europe, requires additional power generation capacity, which will be under-utilised during the rest of the year, entailing higher supply costs.
- New evidence regarding implications during summer on inland waterways (decreased access) and long range ocean transport (increased access).
- Housing will be affected, with increased overheating under no adaptation and damage from subsidence and flooding. Passive cooling measures alone are unlikely to be sufficient to address adaptation in all regions and types of buildings. Retrofitting current housing stock will be expensive.
- An emerging concern is the vulnerability of cultural heritage, including monuments/buildings and cultural landscapes. Some cultural landscapes will disappear. Grape production is highly sensitive to climate, but production (of grape varieties) is strongly culturally-dependent and adaptation is potentially limited by the regulatory context.
- Terrestrial and freshwater species are vulnerable from climate-change shifts in habitats. There is new evidence that species cannot populate new habitat due to habitat fragmentation (urbanization). Observed migration rates are less than that assumed in modelling studies. There are legal barriers to introducing new

species (e.g. forest species in France). New evidence that phenological mismatch will cause additional adverse effects on some species.

- Good evidence that climate change will increase distribution and seasonal activity of pests and diseases. Limited evidence that such effects already occurring. Increased threats to plant and animal health. Public policies are in place to reduce pesticide use in agriculture use and antibiotics in livestock, and this will increase vulnerability to the impact of climate change on agriculture and livestock production.
- Extreme events affect multiple sectors and have the potential to cause a systemic impact. Past events indicate the vulnerability of transport, energy agriculture, water resources and health systems. Resilience to very extreme events varies by sector, and by country.
- A positive (and emerging) effect that may reduce vulnerability is that many European governments (and individual cities) have become aware of the need to adapt to climate change and so are developing and/or implementing adaptation strategies and measures.
- Lack of institutional frameworks is a major barrier to adaptation governance. In particularly, the systematic failure in land use planning policy to account for climate change.

[INSERT TABLE 23-5 HERE
Table 23-5: Multi-sectoral impacts of climate extremes during the last decade in Europe.]

23.10.2. Effects of Observed Climate Change in Europe

Table 23-6 summarises the evidence with respect to key indicators in Europe for the detection of a trend and the attribution of that trend to observed changes in climate factors. The attribution of local warming to anthropogenic climate change is less certain (see Chapter 18 for a full discussion). Further and better quality evidence since 2007 supports the conclusion of AR4 (Europe chapter, Alcamo et al., 2007) that climate change is affecting land, freshwater and marine ecosystems in Europe. Climate warming has caused advancement in the life cycles of many animal groups, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies (see WGII chapter 4 and review by Feehan *et al.* (2009). There is limited evidence that observed climate change is already affecting agricultural, forest and fisheries productivity (see 23.4).

The frequency of river flood events, and annual flood and windstorm damages in Europe have increased over recent decades, but this increase is mainly due to increased exposure and the contribution of observed climate change is unclear (high confidence – based on robust evidence and high agreement)(SREX 4.5.3, (Barredo, 2010). The observed increase in the frequency of hot days and hot nights (high confidence, WGI) is likely to have increased heat-related health effects in Europe (medium confidence), and well as a decrease in cold related health effects (medium confidence) (Christidis *et al.*, 2010). Multiple impacts on health, welfare and economic sectors were observed due to the major heat wave events of 2003 and 2010 in Europe (Table 23-5) (see Chapter 18 for discussion on attribution of events).

[INSERT TABLE 23-6 HERE
Table 23-6: Observed changes in ecological and human systems.]

23.10.3. Key Knowledge Gaps and Research Needs

There is a clear mismatch between the volume of scientific work on climate change since the AR4 and the insights and understanding required for policy needs.

Some specific research needs have been identified:

- More research on co-benefits and unintended consequences of adaptation options, and the effects of adaptation in one sector on other sectors in Europe. For example, air conditioning.
- Improved economic tools and methods for costing and valuation of specific adaptation options including the use of this information in decision making.

- Synergies and trade-offs between mitigation and adaptation need to be further researched and incorporated into economic analyses of the mitigation costs.
- Effects of climate change on infrastructure and the built environment, in the context of adaptation and mitigation policies.
- Impacts from high end climate change (above 4°C), with a lack of impact studies in Europe.
- Resilience of cultural landscapes and communities, and how to manage adaptation, particularly low technology (productively marginal) landscapes
- Climate change impact on ecosystem services (including valuation of ecosystem services) and how this would contribute to the improvement of management of natural resources.
- Development /improvement of regional climate services (seasonal, decadal forecasts)
- Impact of climate change on rural development in order to inform policy in this area.
- Capacity of local and national government to respond to climate change.
- Information on governance (including local and national institutions) for adaptation in the built environment, and infrastructure, including flood defences, over-heating, urban planning.
- More research on the assessment and quantification of climate for tourism, as well as on the response of tourists to past and future marginal climatic conditions for tourism.
- More research on the impacts of climate change on transport, especially on the vulnerability of road and rail infrastructure in different regions, and on the contribution of climatic and non-climatic parameters in the vulnerability of air transport (e.g. changes in air traffic volumes, airport capacities, air traffic demand, weather at the airports of origin, intermediate and final destination).
- [needs to be more specific] Better characterization of the determinants of changes in yield and food quality and improvement of technologies for precision farming.
- Research on the resilience/vulnerability of populations to extreme events, including responses to flood and heat wave risks.
- Development of better risk models for vector borne disease, including public health implications and for animal diseases.

A major barrier to research is lack of access to data, which is also variable across regions and countries, specifically socio-economic data, climate data, forestry, routine health data. Reasons include: government agencies require commercialisation, inappropriate confidentiality. There is a need for long term monitoring of environmental and social indicators and to ensure open and access to data (environment, crop, etc) for long term and sustainable research programmes. Cross-regional cooperation could also ensure compatability and consistency of parameters across the region.

Frequently Asked Questions

FAQ 23.1: Will I still be able to live on the coast in Europe?

It depends where you want to live (and when). Coastal areas are affected by storm surges that will increase in frequency and extent due to sea level rise. Most of this increase in risk will occur after the middle of this century. Models of the coast line suggest that populations in the north western region of Europe are most affected and many countries will need to strengthen their coastal defences (including the Netherlands, Germany, France, Belgium, Denmark, Spain and Italy). The decision to protect an area of coastline will depend on the value (market and non-market values) of the land, its infrastructure or economic productivity, and its conservation potential (valuing species or ecosystems). Some countries have already raised their coastal defence standards. More innovative options (than defence or abandonment) are also being explored such as to adapt dwellings and commercial buildings to occasional flooding. Upgrading coastal defenses can significantly reduce (but not fully eliminate) adverse impacts of sea level rise but coasts are also faced with erosion, excessive development, and other types of environmental degradation not related to climate change. The combination of raised sea defences and coastal erosion may lead to narrower coastal zones in the North Sea, the Iberian coast, and Bay of Biscay.

FAQ 23.2: Will climate change introduce new infectious diseases into Europe?

New (emerging) diseases appear all the time and current diseases change distribution or prevalence (increases and decreases). The factors that determine whether a disease changes distribution include: importation from increased

international travel of persons, vectors or hosts, changes in vector or host susceptibility, drug resistance, climate change, and land use or other habitat changes that affect vectors or hosts. Tropical diseases is a term used to describe diseases that are now only present in the tropics, but malaria was once endemic in Europe and its mosquito vectors are still present. Malaria is not established in Europe despite imported cases because infected persons are quickly detected and treated. Maintaining health surveillance is therefore extremely important. Finally, when an outbreak has occurred (i.e. the introduction of a new disease) determining the causes is very difficult. It is likely that a combination of factors will be important. A suitable climate is a necessary but not a sufficient factor for the introduction of new infectious diseases.

FAQ 23.3: Will Europe need to import more food because of climate change?

Agriculture is the most dominant European land use, accounting for almost half of the total EU27 land area. Europe is one of the world's largest and most productive suppliers of food and fibre, but also imports large amounts of agricultural commodities. A reduction in crop yields, particularly wheat in southern Europe, is expected under future climate scenarios. A shift in cultivation areas of added-value crops, such as wine, may also occur. Loss of food production may be compensated by increases in other European sub-regions, under normal climate variability and long term changes. However, if ability of the European market to sustain climate shock events is impaired, the region would require exceptional food importation.

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Table 23-1: Projected Changes of Selected Climate Parameters and Indices[1] for the Period 2071-2100 with Respect to 1971-2000 Spatially Averaged for Europe Sub-regions. The likely range defines the range of 66% of all projected changes around the ensemble median.

A) A1B scenario. Numbers are based on 9 (indicated with *) and 20 (indicated with **) regional model simulations taken from EU-ENSEMBLES project for the SRES A1B emission scenario.

Scenario A1B	Climate Parameters	Measure	Alpine	Atlantic	Continental	Northern	Southern
2071-2100 minus 1971-2000	**Mean annual temperature** in K [xx]	***Median***	***3,4***	***2,5***	***3,3***	***3,8***	***3,6***
		Min	2,8	1,9	2,1	3,2	2,3
		Likely in the range	**3,1 to 4,5**	**2,1 to 3,5**	**2,8 to 4,5**	**3,5 to 5,0**	**3,3 to 4,1**
		Max	5,4	4,7	5,7	5,8	5,5
	Frost days (1) per year [x]	***Median***	***-50***	***-24***	***-44***	***-54***	***-24***
		Min	-37	-13	-26	-38	-12
		Likely in the range	**-38 to -57**	**-15 to -34**	**-27 to -53**	**-40 to -55**	**-12 to -31**
		Max	-72	-39	-56	-71	-34
	Summer days (2) per year [x]	***Median***	***14***	***21***	***32***	***7***	***48***
		Min	4	9	21	3	33
		Likely in the range	**11 to 20**	**16 to 32**	**22 to 41**	**5 to 14**	**33 to 51**
		Max	21	34	43	27	51
	Tropical nights (4) per year [x]	***Median***	***3***	***8***	***21***	***4***	***47***
		Min	1	2	14	1	18
		Likely in the range	**2 to 9**	**6 to 17**	**16 to 35**	**1 to 7**	**35 to 52**
		Max	11	32	43	10	60
	Growing season length (5) days per growing season [xx]	***Median***	***47***	***41***	***52***	***41***	***36***
		Min	27	23	20	25	14
		Likely in the range	**34 to 56**	**33 to 51**	**33 to 62**	**27 to 46**	**27 to 41**
		Max	75	55	81	61	51
	Warm spell duration index (14) days per year [x]	***Median***	***57***	***44***	***42***	***67***	***91***
		Min	46	29	26	37	67
		Likely in the range	**51 to 84**	**35 to 72**	**37 to 69**	**47 to 96**	**85 to 112**
		Max	126	125	94	119	144
	Cold spell duration index (15) days per year [x]	***Median***	***-5***	***-5***	***-6***	***-6***	***-5***
		Min	-4	-4	-4	-5	-3
		Likely in the range	**-4 to -5**	**-4 to -6**	**-5 to -6**	**-5 to -8**	**-4 to -5**
		Max	-8	-9	-9	-9	-8
	Annual total precipitation (27) in % [xx]	***Median***	***7***	***3***	***3***	***16***	***-15***
		Min	1	9	-9	4	-7
		Likely in the range	**5 to 12**	**-4 to 5**	**-1 to 5**	**13 to 21**	**-12 to -18**
		Max	15	-11	12	29	-25
	Annual total precipitation where RR>99p of 1971/2000 (26) in % [xx]	***Median***	***57***	***65***	***53***	***64***	***43***
		Min	35	28	31	32	21
		Likely in the range	**47 to 68**	**42 to 98**	**44 to 77**	**47 to 88**	**35 to 57**
		Max	117	112	110	105	74

[1] Index definition from http://cccma.seos.uvic.ca/etccdi/list_27_indices.shtml

B) RCP4.5 scenario. Numbers are based on 7 (indicated with *) and 8 (indicated with **) regional model simulations taken from EURO-CORDEX project for the RCP 4.5 emission scenario.

Scenario RCP 4.5	Climate Parameters	Measure	Alpine	Atlantic	Continental	Northern	Southern
2071-2100 minus 1971-2000	**Mean annual temperature** in K [x]	***Median***	***2,3***	**1,7**	**2,0**	**2,8**	**2,0**
		Min	1,8	1,3	1,6	2,0	1,9
		Likely in the range	**1,9 to 2,6**	**1,4 to 1,7**	**1,6 to 2,3**	**2,0 to 3,1**	**1,9 to 2,1**
		Max	3,4	2,1	3,2	4,3	2,7
	Frostdays (1) per year [xx]	***Median***	***-39***	***-27***	***-34***	***-35***	***-20***
		Min	-25	-12	-16	-24	-10
		Likely in the range	**-26 to -41**	**-15 to -30**	**-18 to -38**	**-26 to -41**	**-11 to -25**
		Max	-47	-30	-40	-52	-29
	Summerdays (2) per year [xx]	***Median***	***8***	***11***	***20***	***4***	***27***
		Min	3	6	11	2	21
		Likely in the range	**4 to 11**	**7 to 14**	**13 to 24**	**2 to 13**	**25 to 33**
		Max	18	33	28	16	36
	Tropicalnights (4) per year [xx]	***Median***	***1***	***4***	***10***	***1***	***23***
		Min	0	0	2	0	7
		Likely in the range	**1 to 3**	**3 to 5**	**9 to 27**	**0 to 5**	**18 to 25**
		Max	8	18	30	7	41
	Growing season length (5) days per growing season [x]	***Median***	***25***	***36***	***22***	***19***	***24***
		Min	23	24	17	17	16
		Likely in the range	**23 to 35**	**27 to 40**	**20 to 29**	**19 to 27**	**17 to 31**
		Max	39	45	41	33	38
	Warm spell duration index (14) days per year [xx]	***Median***	***36***	***21***	***24***	***37***	***37***
		Min	27	18	18	22	30
		Likely in the range	**28 to 59**	**19 to 29**	**18 to 44**	**23 to 45**	**33 to 73**
		Max	70	56	53	65	83
	Cold spell duration index (15) days per year [xx]	***Median***	***-5***	***-4***	***-5***	***-6***	***-4***
		Min	-3	-4	-4	-5	-3
		Likely in the range	**-4 to -6**	**-4 to -5**	**-4 to -6**	**-6 to -7**	**-3 to -4**
		Max	-7	-6	-7	-7	-6
	Annual total precipitation (27) in % [x]	***Median***	***5***	***1***	***9***	***10***	***-6***
		Min	3	-1	0	7	-11
		Likely in the range	**4 to 7**	**-1 to 4**	**1 to 13**	**8 to 14**	**-10 to 0**
		Max	12	9	16	22	0
	Annual total precipitation where RR>99p of 1971/2000 (26) in % [x]	***Median***	***53***	***36***	***46***	***43***	***36***
		Min	24	20	17	27	23
		Likely in the range	**25 to 61**	**25 to 67**	**33 to 60**	**28 to 65**	**31 to 55**
		Max	73	73	74	70	62

Table 23-2: Assessment of climate change impacts on ecosystem services by sub-region and sector. Assessment assuming medium economic development, with land use change and no planned adaptation.

	Southern	Atlantic	Continental	Northern	Alpine
Provisioning services:					
Food production	Decreasing	Increasing to decreasing	No change to decreasing	Increasing to decreasing	Increasing to decreasing
Livestock production	Decreasing	Increasing to decreasing	Decreasing	Increasing	Increasing to decreasing
Fibre production					Decreasing
Bioenergy production	Decreasing			Increasing	Increasing
Fisheries production	No change to decreasing	No change to decreasing	Decreasing	No change to decreasing	
Timber production	Decreasing	No change to increasing	Increasing to decreasing	Increasing	Increasing to decreasing
Non-wood forest products	Decreasing			No change to increasing	
Regulating services:					
Climate regulation (carbon sequestration)					
- General/forests	Increasing to decreasing	No change to increasing	No change to increasing	Increasing to decreasing	Increasing
- Wetland	No change to decreasing	No change to decreasing	Decreasing	No change to decreasing	
- Soil carbon stocks	Decreasing	Increasing to decreasing	Decreasing	Decreasing	Decreasing
Pest control	Decreasing		Increasing	Increasing	Increasing
Natural hazard regulation					
- Forest fires regulation	Decreasing	Decreasing*	Decreasing*		
- Erosion, avalanche, landslide regulation					Increasing to decreasing
- Flooding regulation					Decreasing
- Drought regulation	Decreasing		No change to decreasing		
Water quality regulation		Decreasing		Decreasing	
Cultural services:					
Recreation (fishing, nature enjoyment)	Decreasing	Decreasing		Increasing to decreasing	Decreasing
Tourism (skiing)				Decreasing	Increasing
Aesthetic/heritage (landscape character, cultural landscapes)	Decreasing	Decreasing	No change to decreasing		Decreasing
Biodiversity	Decreasing	Increasing to decreasing	Decreasing	Increasing to decreasing	

* Forest fires or moorland wildfires increase

Table 23-3: Selected published adaptation cost estimates for European countries.

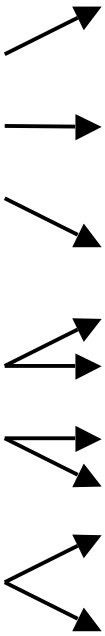
Population	Cost estimate	Time period	Sectors/Outcomes	Reference
Europe	€2.5–5 billion/a	By 2080s	Coastal protection	Brown et al., submitted b
Europe	€1.7 billion/a €3.4 billion/a €7.9 billion/a	By 2020s By 2050s By 2080s	Protection from river flood risk	Rojas et al., submitted
Netherlands	€1.2–1.6 billion/a €0.9–1.5 billion/a	up to 2050 2050–2100	Protection from coastal and river flooding	Delta Committee, 2008
Sweden	total of up to €10 billion	over period 2010-2100	Multi sector	Swedish Commission on Climate and Vulnerability, 2007
Greece	170-770 million €	2071-2100	Higher electricity generation cost resulting from higher summer energy demand for cooling	Mirasgedis et al., 2007
Cyprus	239 million €	2010-2030	Higher electricity generation cost resulting from higher summer energy demand for cooling	Zachariadis, 2010
Spain	8.8-30.6 million €/a	2008-2050	Higher costs to electricity users and costs paid in the carbon market (emissions trading)	Pilli-Sihvola et al., 2010
Europe (Rhine river)	194-263 million €	Future climatic conditions similar to those of 2003	Higher transport prices for goods as a result of load restrictions on inland ships (due to low river water levels in summer)	Jonkeren, 2009

Table 23-4: Assessment of climate change impacts by sub-region and sector (by 2050, medium emissions)
With economic development, with land use change. No further planned adaptation.

	Alpine	Southern	Northern	Continental	Atlantic	
Infrastructure						
Wind energy production		[1]				23.3.4
Hydropower generation	[2]					23.3.4
Thermal power production						23.3.4, 8.2.3.2
Energy consumption (net annual change)						23.3.4, 23.8.1
Road accidents [3]						23.3.3
Rail delays (weather-related)	?	?		?	[4]	23.3.3, 8.3.3.6
Load factor of inland ships	?	?	?			23.3.3
River flood damages	?	?	?			23.3.1
Transport time and cost in ocean routes	?	?			?	23.3.3, 18.3.3.3.5
Length of ski season		?			?	23.3.6, 3.5.7
Food and Fibre production						
Wine production	?		?			23.3.5, 18.3.3.1, 23.4.1
Arable Production						23.4.1
Livestock production						23.4.2
Water availability for agriculture						23.4.3
Forest productivity	?			?		23.4.4
Pest and plant diseases						23.4.1, 23.4.4
Bioenergy production	?			?	?	23.4.5
Health and Social Impacts						
Heat wave mortality						23.5.1

Damage on cultural buildings	↗	↗↘	↗	↗	↗	23.5.4
Decreasing						
Loss of cultural landscapes	↗	?	↗	↗	↗	23.5.4
A range from no change to increasing			**Enviromental quality**			
Air quality (ozone background levels)	?	?	?	?	?	23.6.1
A range from no change to decreasing						
Water quality	→	↘	→	→	↘	23.6.3
Local loss of native species and extinction of species	↗	↗	↗	↗→	↗	23.6.4
A range from increasing to decreasing						

Code. Green means a “beneficial change” and Red means a “harmful”, ? No relevant literature found



FOOTNOTES

[1] Simulations have been performed, but mostly for the period after 2070.

[2] The increasing trend is for Norway.

[3] The decreasing trend refers mainly to the number of severe accidents.

[4] Impacts have been studied and quantified for UK only. The increasing trend stands for summer delays and the decreasing trend for winter delays.

[5] In both seasons, no significant impacts are expected by 2020, while more substantial changes are expected by 2080. For 2050 impacts are assumed to vary linearly (although this may not be the case).

[6] The constant trend stands for the Mediterranean, where some studies estimate no changes due to climate change at least until 2030 or even 2060.

Table 23-5: Multi-sectoral impacts of climate extremes during the last decade in Europe.

Year	Region	Meteorological Event/ Breaking Record*	Production Systems and Physical Infrastructure, settlements	Agriculture, Fisheries, Forestry, Bioenergy	Health and Social Welfare	Environmental Quality and Biological Conservation
2003	Europe	Hottest summer in at least 500 years (Luterbacher *et al.*, 2004)	Damage to road and rail transport systems. Reduced/ interrupted operation of nuclear power plants (mostly in France). High transport prices in Rhine due to low water levels.	Grain harvest losses of 20% (Aerts and Botzen, 2011)	Approx 35,000 deaths in August in Central and Western Europe (Robine *et al.* 2008)	Water quality. High outdoor pollution levels. (EEA 2012)
2004/ 2005	Iberian Peninsula	Hydrological drought		Grain harvest losses of 40% (EEA, 2010b)		
2007/ 2008	England and Wales, Southern Europe	May–July wettest since records began in 1766. Hottest summer on record in Greece since 1891 (Founda & Giannakopoulos 2009)	Disruption, economic loss and social distress turned the summer 2007 floods into a national catastrophe. Broad-scale estimated total losses were £4 billion (Chatterton et al. 2010),	Social distress.		
2010	Western Russia	Hottest summer since 150 (Barriopedro *et al.*, 2011)		Fire damage to forests. Crop yields	Heat mortality in Moscow region (Revich and Shaposhnikov, 2010)	High outdoor pollution levels. (Revich and Shaposhnikov, 2010.
2011	France	Hottest and driest spring on record in France since 1880	Reduction on snow cover for skiing	Decline in crop yields. (AGRESTE, 2011)		

* based on Coumou and Rahmstorf, 2012.

Table 23-6: Limits to Adaptation Measures in Europe.

Area/Location	System	Adaptation measures	Limits to adaptation measure(s)	References
Low altitude/ small-size ski resorts	Ski tourism	Artificial snowmaking	Climatic, technological and environmental constraints Economic viability Social acceptability of charging for previously free skiing. Social acceptability of alternatives for winter sport/leisure.	(Landauer et al., 2012) (Steiger, 2010a; Steiger, 2010b) (Steiger and Mayer, 2008)(Unbehaun et al., 2008)
Thermal power plants/ cooling through river intake and discharge	Once-through cooling systems	Closed- circuit cooling	High investment cost for retrofitting existing plants	(van Vliet et al., 2012)(Koch and Vögele, 2009)(Hoffman et al., 2013)
Rivers used for freight transport	Inland transport	Reduced load factor of inland ships	Increased transport prices (Rhine and Moselle market)	(Jonkeren, 2009) (Jonkeren et al., 2007)
		Use of smaller ships	Existing barges below optimal size (Rhine)	(Demirel, 2011)
Agriculture, Northern and Continental Europe.	Arable crops	Sowing date as agricultural adaptation	Other constraints (e.g. frost) limit farmer behaviour	(Oort, 2012).
Agriculture, Northern and Continental Europe.	Arable crops	Irrigation	Groundwater availability, competition with other users.	(Olesen *et al.*, 2011)
Agriculture, Viticulture	High value crops	Change distribution	Legislation on cultivar and geographical region	Box 23-1
Conservation Cultural landscapes	Alpine meadow/	Extend habitat	No technological adaptation option.	(Engler *et al.*, 2011) (Dullinger *et al.*, 2012)
Conservation of species richness	Movement of species	Extend habitat	Landscape barriers and absence of climate projections in selection of conservation areas.	(Butchart et al., 2010) (Araújo *et al.*, 2011; Filz *et al.*, 2012; Virkkala *et al.*, 2013).
Forests	Movement of species and Productivity reduction	Introduce new species	Not socially acceptable, Legal barriers to non-native species	(Giuggiola *et al.*, 2010; Hemery *et al.*, 2010; García-López J.M. and Alluéa, 2011) (Casalegno *et al.*, 2007)
Forests	Fire incidence	landscape planning and fuel reduction	Higher flammability due to warmer and drier conditions	(Moreira *et al.*, 2011).

Table 23-6: Impact of observed changes in key indicators in ecological and human systems

Indicator	*Change in indicator*	*Confidence in detection*	*Confidence in attribution to change in climate factors [**]*	*Key references*	*Section*
Infrastructure, etc.					
Storm losses in Europe	Increase since 1970s	Increasing trend (high confidence)	No causal role for climate	Barredo, 2010	23.3.7
Hail losses	Increase in parts of Germany	Increasing trend (low confidence)	No causal role for climate	Kunz *et al.*, 2009	23.3.7
Flood losses	Increasing general trend in economic losses in Europe since 1970s; none in some locations	Increasing trend (medium confidence)	No causal role for climate	Barredo, 2009; Barredo et al., 2012	23.3.1
Agriculture					
Agriculture	CO2 induced positive contribution to yield since preindustrial for C3 crops	High confidence (high agreement, robust evidence)	High confidence (high agreement, robust evidence)	Amthor, 2001; Long *et al.*, 2006; McGrath and Lobell, 2011	7.2.1
Agriculture	Stagnation of wheat yields in some countries in recent decades	High confidence	Medium confidence	Lobell *et al*. 2011 ; Brisson et al., 2010; Kristensen et al., 2011	23.4.1
Phenology	Earlier greening, Earlier leaf emergence and fruit set in temperate and boreal climate,	High confidence (high agreement, robust evidence)	High confidence (high agreement, robust evidence)	Menzel *et al.*, 2006	4.4.1.1
Ocean systems	Increased phytoplankton productivity in NE. Atlantic, decrease in warmer regions, due to warming trend and hydroclimatic variations	High confidence	Medium confidence	Beaugrand *et al.*, 2002; Edwards and Richardson, 2004	6.3.2
Ocean systems	Northward movement of species and increased Species richness due to warming trend	High confidence	Medium confidence	Philippart *et al.* , 2011	6.3.2
Health and Social Welfare					
Atopic disease	Increased allergic sensitization to pollens	Very low confidence (single study)	Very low confidence	Ariano *et al.* 2010	11.4
Cold-related mortality	Decline in cold related mortality in England and Wales	Low confidence (confounding)	Low confidence	Christidis et al. 2010	11.4
Environmental quality and biodiversity					
Biodiversity	Increased number of colonization events by alien plant species in Europe	Medium confidence (high agreement, medium evidence)	Medium confidence	Walther *et al.*, 2009	4.2.4.7
Migratory birds	Earlier arrival of migratory birds in Europe over the 1970/2000 period	Medium confidence (medium agreement, medium evidence)	Medium confidence	Moller *et al.*, 2008	4.4.1.1
Tree spices	Upward shift in tree line in	Medium evidence	Medium confidence	Gehrig-Fasel *et*	18.3.

	Europe	(medium agreement, high evidence)		*al.*, 2007, Lenoir *et al.*, 2008	2.1,
Forest fires	Area burnt	Increasing area	High confidence (high agreement, robust evidence)	Camia and Amatulli 2009; Hoinka et al., 2009; Carvalho et al., 2010; Salis et al., in press; Pereira et al., 2005; Koutsias et al., 2012	23.4.4

*[** Note- this is not attribution to anthropogenic forcing. See chapter 18 for a more complete discussion.*

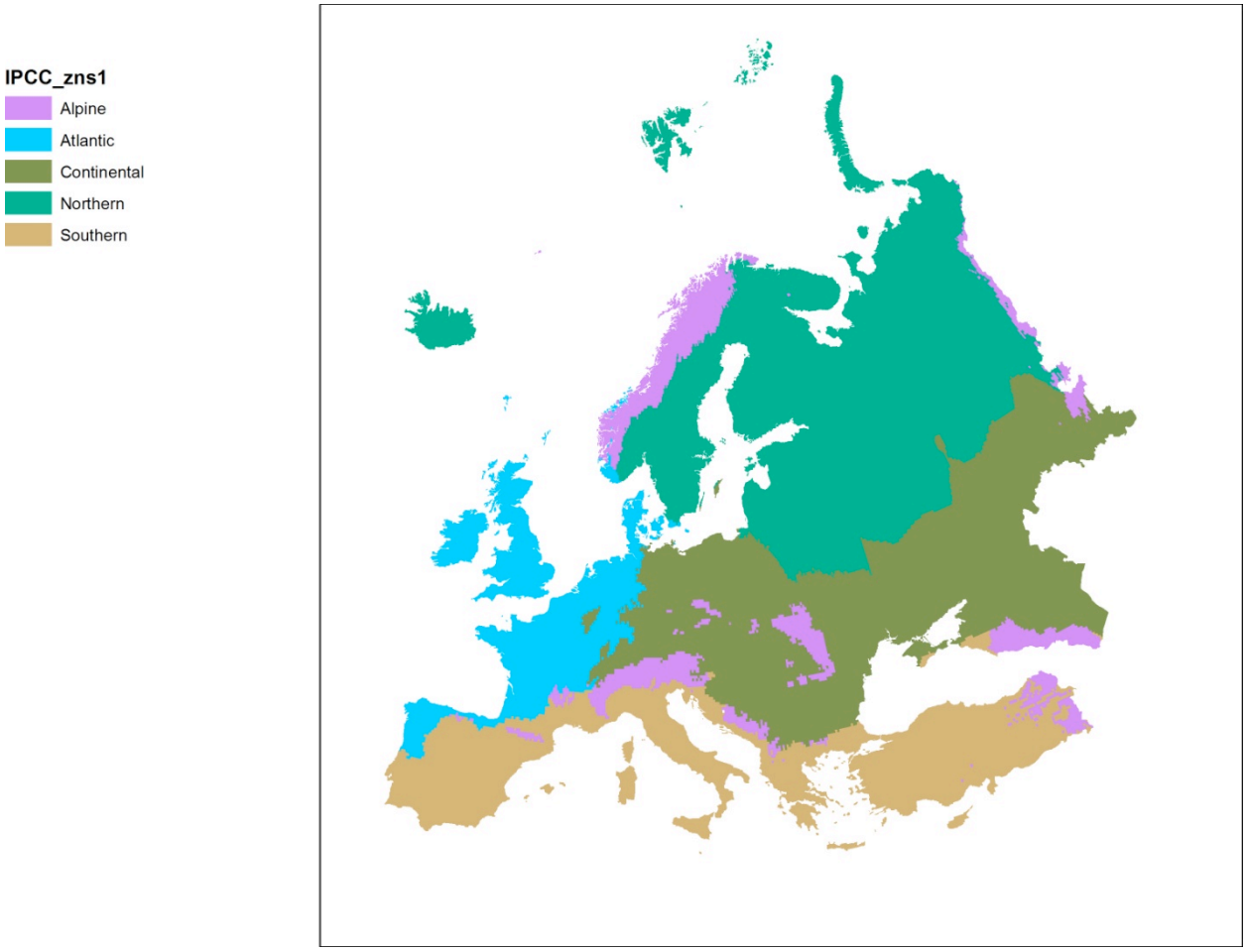
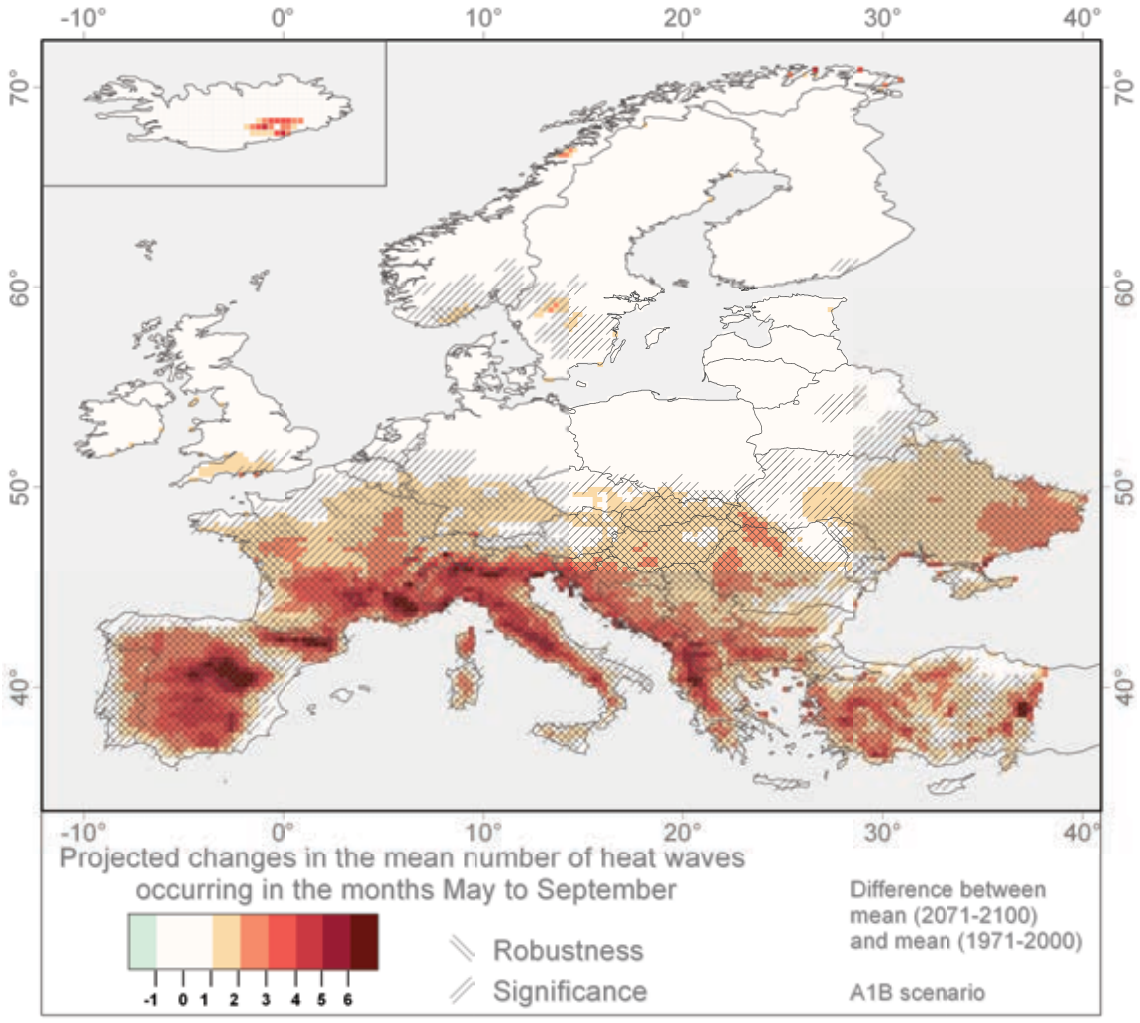


Figure 23-1: Sub-regional classification of the IPCC Europe region. Based on Metzger et al., 2005.

Figure 23-2: Projected changes in the mean number of heat waves occurring in the months May to September for the period 2071-2100 compared to 1971-2000 (number per season) (Jacob et al, 2013). Heat waves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the daily maximum temperature of the May to September season of the control period (1971-2000) by at least 5°C. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test). For the eastern part of Turkey, unfortunately no regional climate model projections are available.

A) Changes represent average over 9 regional model simulations (A1B) taken from the EU-ENSEMBLES project.



B) Changes represent average over 8 regional model simulations (RCP4.5) taken from the EURO-CORDEX project.

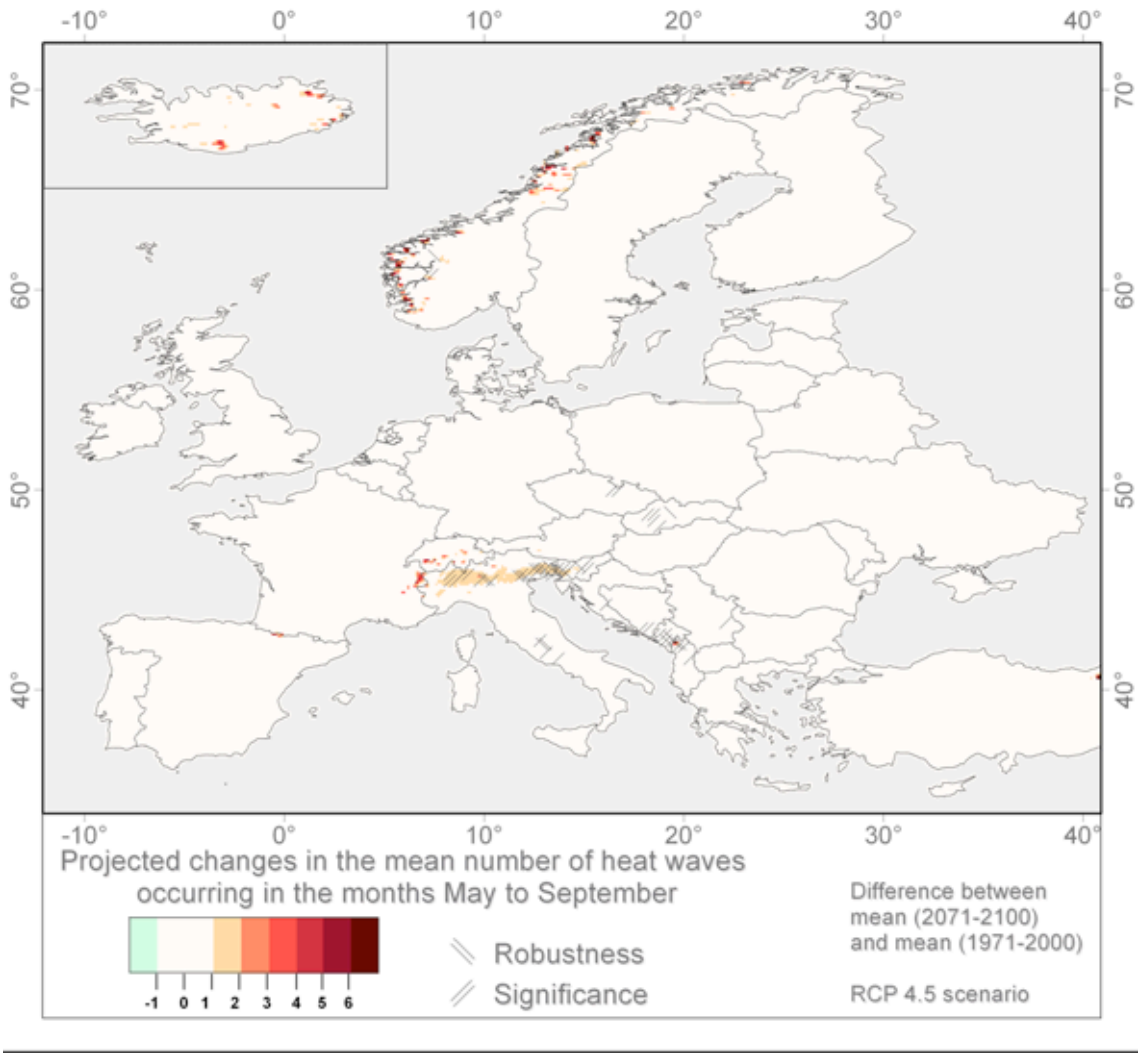
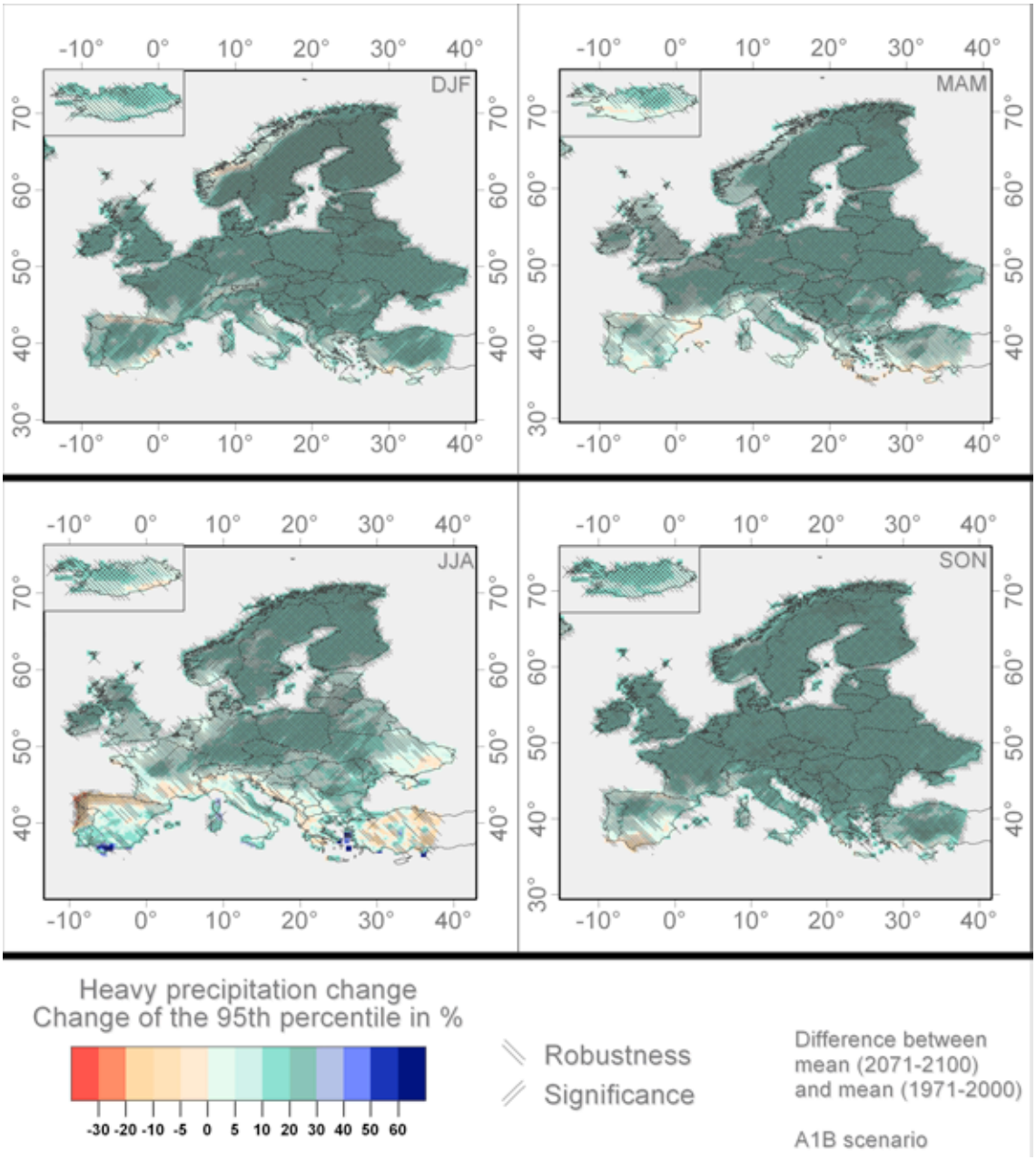


Figure 23-3: Projected seasonal changes of heavy precipitation defined as the 95th percentile of daily precipitation (only days with precipitation > 1mm/day are considered) for the period 2071-2100 compared to 1971-2000 (%) (Jacob et al., 2013). For the eastern part of Turkey, unfortunately no regional climate model projections are available. The figures are sorted as follows: left side: DJF, JJA; right side: MAM, SON. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test).

A) Changes represent average over 20 regional model simulations (A1B) taken from the EU-ENSEMBLES project.



B) Changes represent average over 7 regional model simulations (RCP4.5) taken from the EURO-CORDEX project.

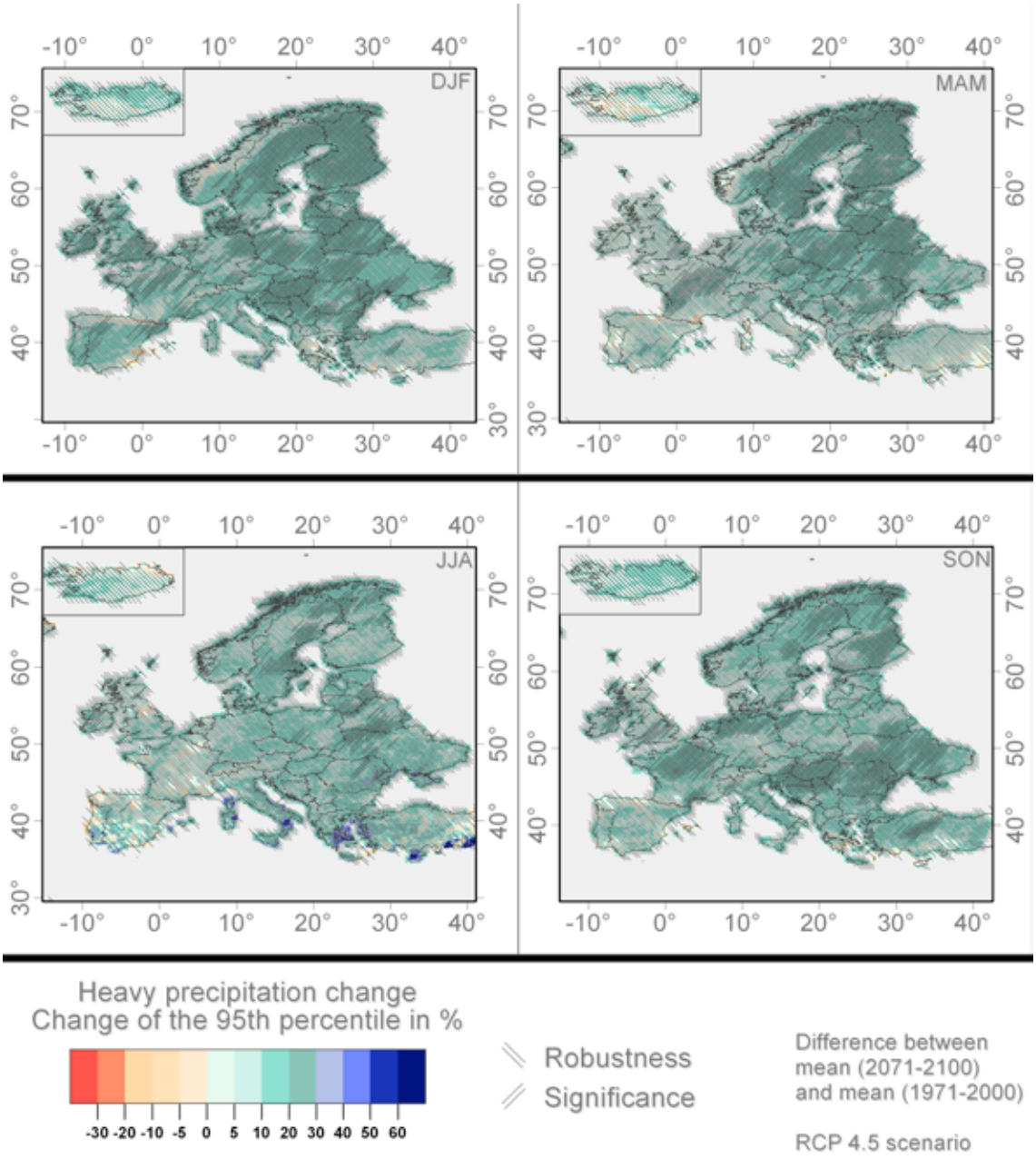
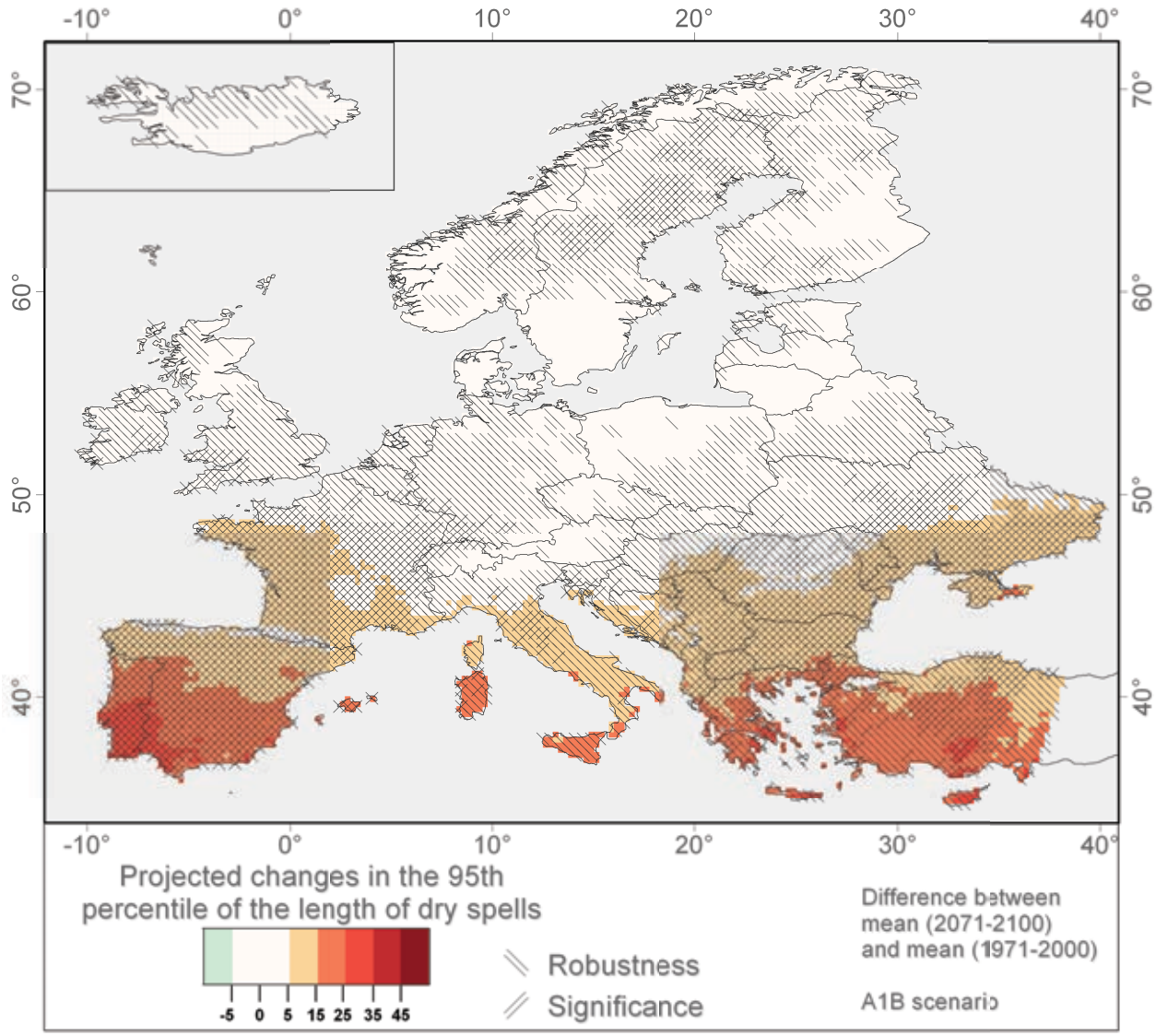


Figure 23-4. Projected changes in the 95th percentile of the length of dry spells for the period 2071-2100 compared to 1971-2000 (in days) (Jacob et al., 2013). Dry spells are defined as periods of at least 5 consecutive days with daily precipitation below 1mm. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test)..For the eastern part of Turkey, unfortunately no regional climate model projections are available .

A) Changes represent average over 20 regional model simulations (A1B) taken from EU-ENSEMBLES project.



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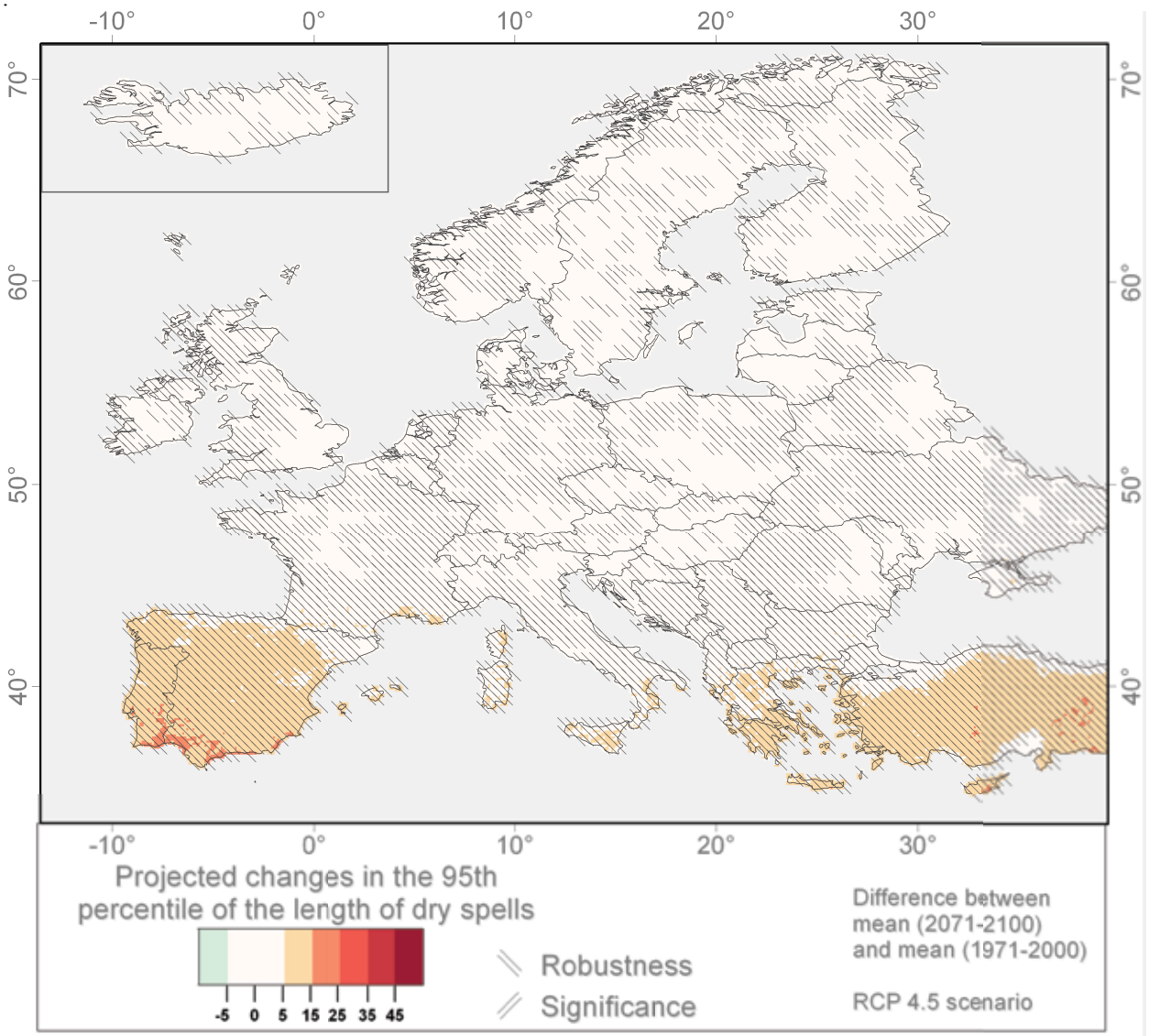

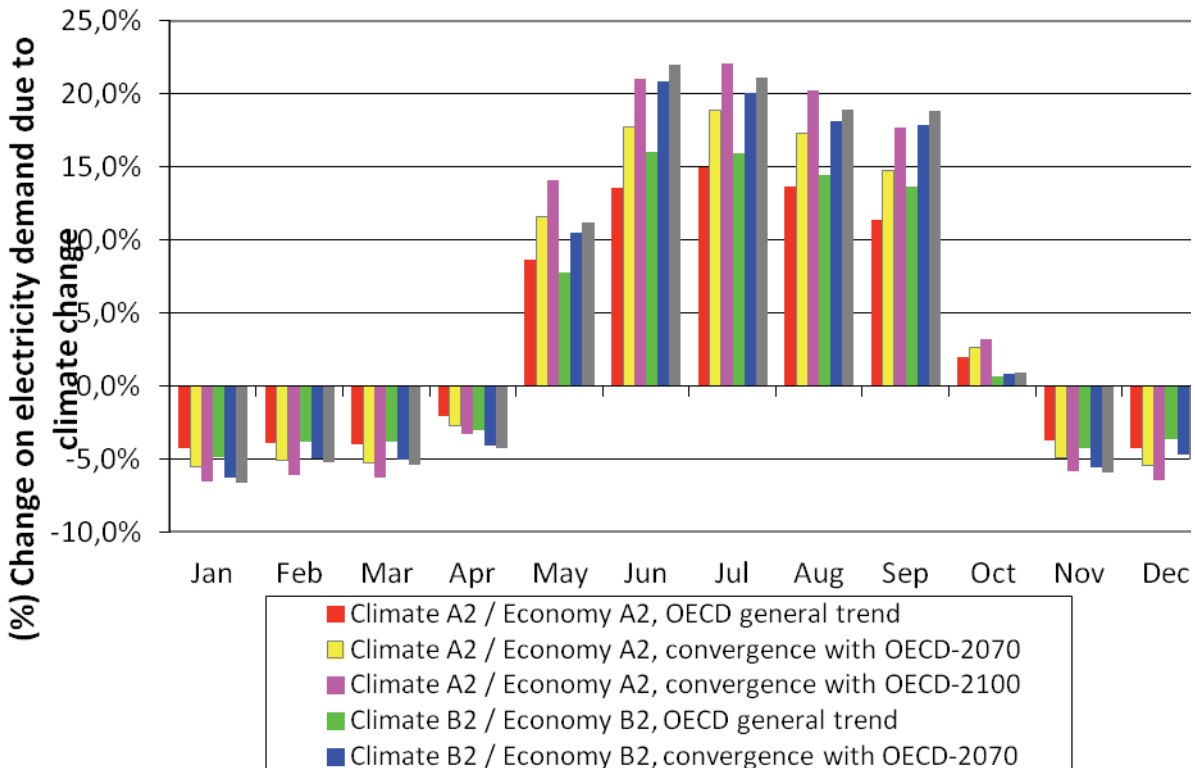

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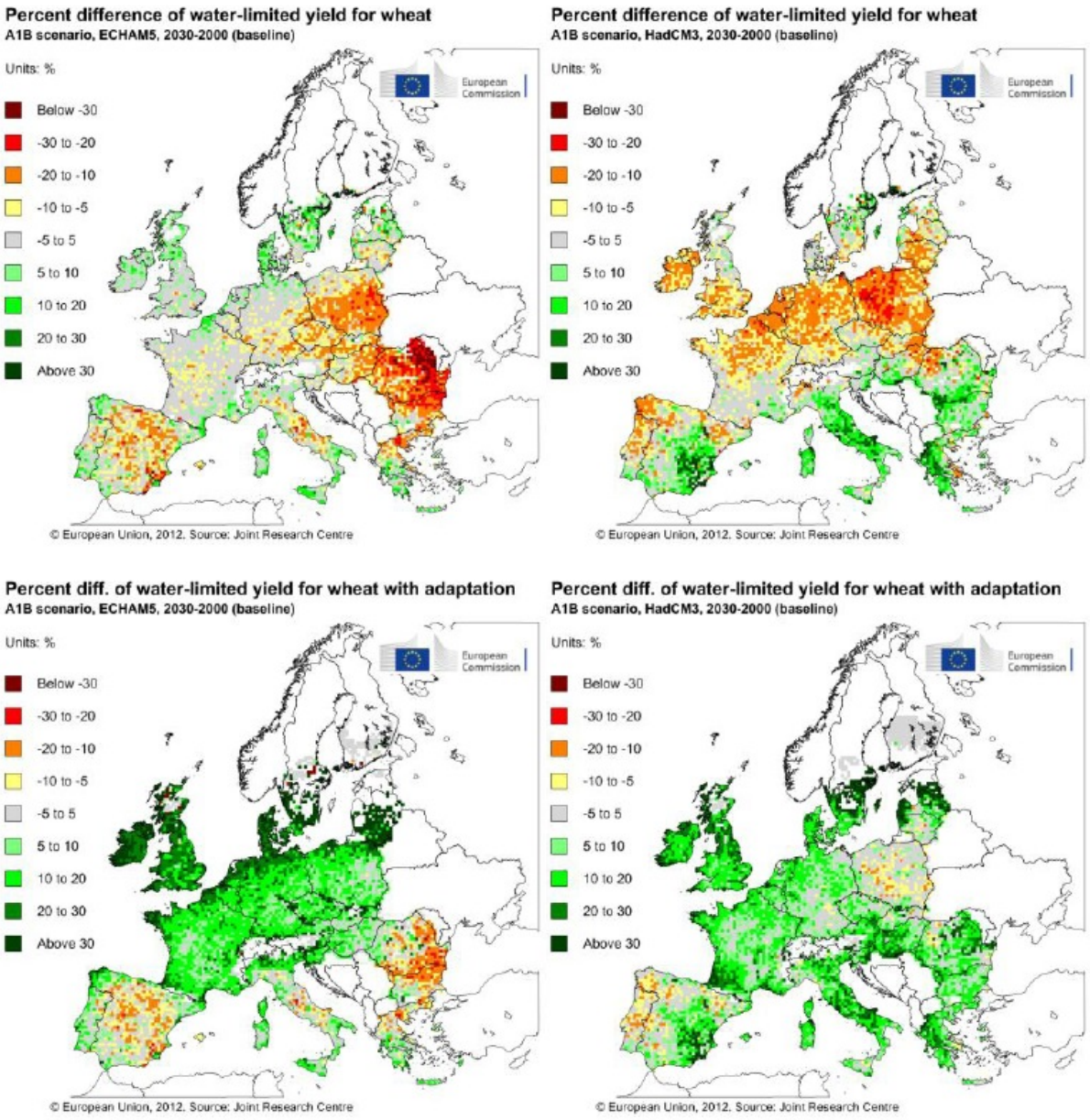

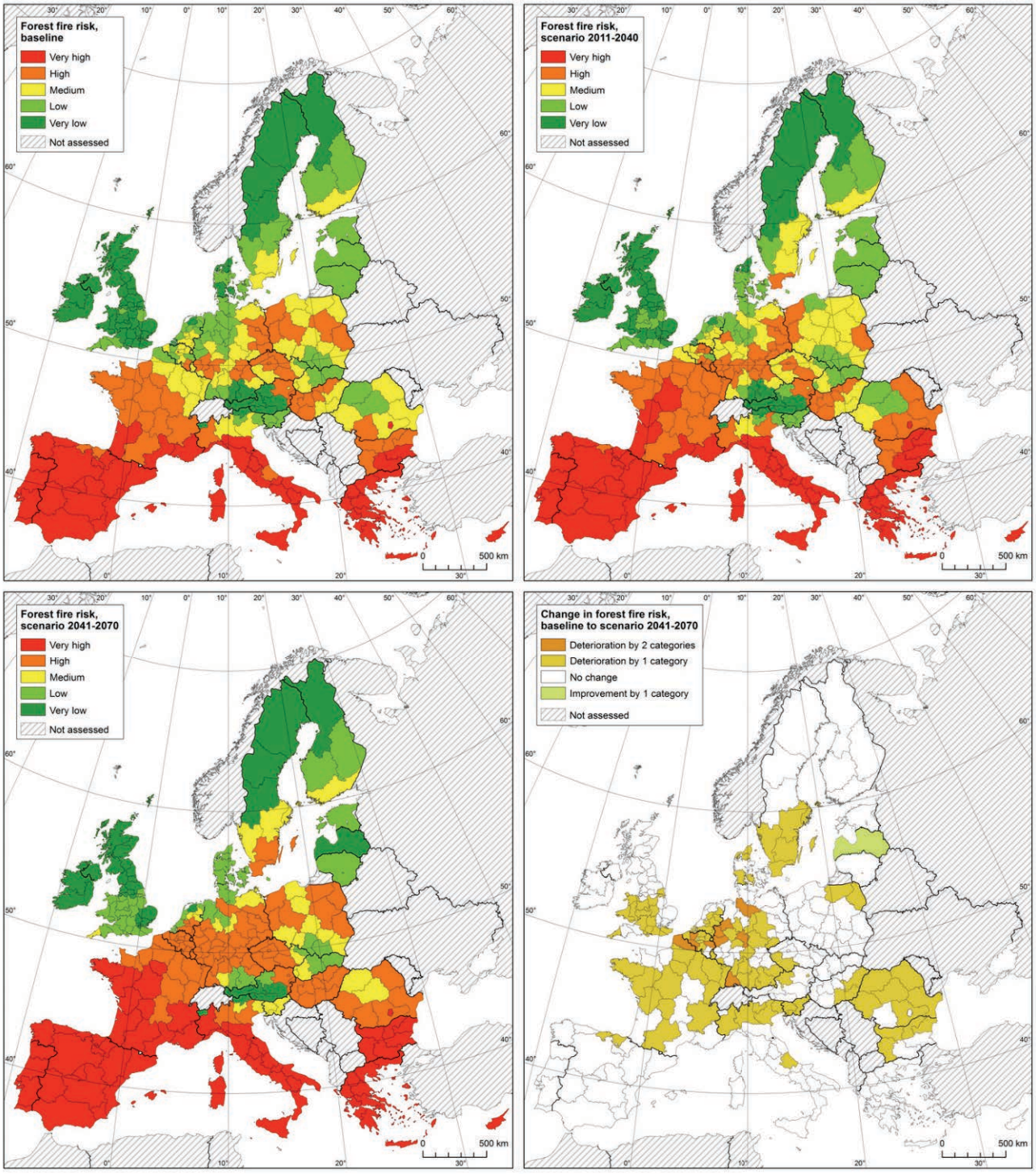

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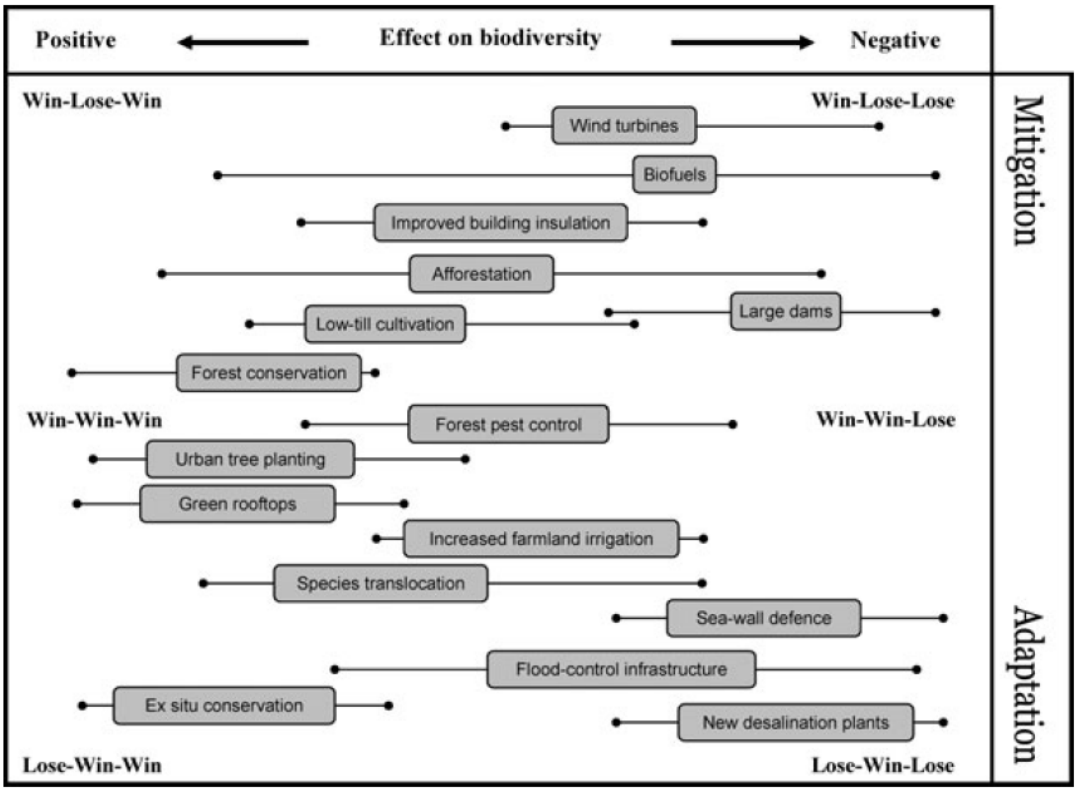

Chapter 24. Asia

Coordinating Lead Authors
Yasuaki Hijioka (Japan), Erda Lin (China), Joy Jacqueline Pereira (Malaysia)

Lead Authors
Richard Thomas Corlett (Singapore), Xuefeng Cui (China), Gregory Insarov (Russian Federation), Rodel Lasco (Philippines), Elisabet Lindgren (Sweden), Akhilesh Surjan (India)

Contributing Authors
Elena M. Aizen (USA), Vladimir B. Aizen (USA), Rawshan Ara Begum (Bangladesh), Kenshi Baba (Japan), Qingxian Gao (China), Monalisa Chatterjee (USA), Masahiro Hashizume (Japan), Manmohan Kapshe (India), Andrey G. Kostianoy (Russia), Sreeja Nair (India), Tran Van Giai Phong (Viet Nam), SVRK Prabhakar (India), Andreas Schaffer (Singapore), Rajib Shaw (Japan), Reiner Wassman (Philippines), Thomas J. Wilbanks (USA), Shaohong Wu (China)

Review Editors
Rosa Perez (Philippines), Kazuhiko Takeuchi (Japan)

Volunteer Chapter Scientist
Yuko Onishi (Japan)

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24.2: How will climate change affect biodiversity and ecosystems in Asia?
24.3: How is climate change affecting permafrost in Asia?
24.4: How will climate change affect food production and food security in Asia?
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Cross-Chapter Box
CC-TC. Case Study Building Long Term Resilience from Tropical Cyclone Disasters

References

Executive Summary

Warming trends and increasing temperature extremes have been observed across most of the Asian region (high confidence) [24.3]. Increasing trends in annual mean temperatures and numbers of warm days, and a decreasing trend in cold days, have been observed across most of the Asian region, including the Tibetan Plateau, during the 20th century, with the warming trend continuing into the new millennium. Annual mean precipitation trends are characterized by strong variability, with both increasing and decreasing trends observed in different parts of Asia.

Water scarcity is expected to be a major challenge for most of the region due to increased water demand and lack of good management (medium confidence) [24.4.3]. Water resources are important in Asia given the massive population. However, there is low confidence in future precipitation projections at a regional scale and thus in freshwater availability in most parts of Asia. Shrinking of glaciers in Central Asia and the Himalayas is projected to affect water resources in downstream river catchments. Population growth and increasing demand arising from higher standards of living could worsen water security in many parts in Asia and affect many people in future. Better water management strategies are needed to ease water scarcity. Water saving technologies and changing to drought tolerant crops have been found to be successful adaptation options in the region.

The impacts of climate change on food production and food security in Asia will vary by region with many regions experiencing a decline in productivity (medium confidence) [24.4.4]. This is evident in the case of rice production. Most models, using a range of GCMs and SRES scenarios, show that higher temperatures will lead to lower rice yields as a result of shorter growing periods and heat-induced sterility. There are a number of regions that are already near the critical temperature threshold. However, CO_2 fertilization may at least in part offset yield losses in rice and other crops. In Central Asia, some areas could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters and slight increase in winter precipitation), while others could be losers (western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase water demand for irrigation, and exacerbate desertification). In the Indo-Gangetic Plains of South Asia there could be an up to 50% decrease in the most favorable and high yielding wheat area due to heat stress at 2x CO_2. There are many potential adaptation strategies, such as crop breeding, but research on their effectiveness is limited.

Terrestrial systems are under increasing pressure from both climatic and non-climatic drivers (high confidence) [24.2.2, 24.4.2, 24.4.3]. The projected changes in climate will impact vegetation and increase permafrost degradation in Asia during the 21st Century. The largest changes are expected in cold northern and high-altitude areas, where boreal and subalpine trees will *likely* invade treeless arctic and alpine vegetation, and evergreen conifers will *likely* invade deciduous larch forest. Large changes may also occur in arid and semi-arid areas, but uncertainties in precipitation projections make these difficult to predict. Vegetation change in the more densely populated parts of Asia will be constrained by the impact of vegetation fragmentation on seed dispersal. The impacts of projected climate changes on the vegetation of the lowland tropics are currently poorly understood. Trends in phenological timing consistent with the impacts of regional warming are widespread in eastern Asia, particularly for plants. Permafrost degradation will spread during the 21st century from the southern and low-altitude margins, advancing northwards and upwards [24.4.2.3]. Many models agree on the direction of change, but rates of change vary greatly between different projections. The Altai-Sayan, Pamir and Tien Shan glaciers have lost on average 10% of their area and 15% of their ice volume since 1960. Rates of further glacier degradation depend mainly on increases in summer air temperature and changes in precipitation [24.9.3].

Coastal and marine systems in Asia are also under increasing pressure from both climatic and non-climatic drivers (high confidence) [24.4.3]. It is very *likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels and in the Asian Arctic there is *high agreement* and *medium evidence* that rising sea-levels will interact with projected changes in permafrost and the length of the ice-free season to cause increased rates of coastal erosion. Coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea-levels**.** Widespread damage to coral reefs correlated with episodes of high sea-surface temperature has been reported in recent decades and there is *high confidence* that such damage will increase during the 21st century as a result of both warming and ocean acidification.

Multiple stresses caused by rapid urbanization, industrialization and economic development will be compounded by climate change (high confidence) [24.4, 24.5, 24.6, 24.7]. Climate change is expected to adversely affect the sustainable development capabilities of most Asian developing countries by aggravating pressures on natural resources and the environment. Development of sustainable cities in Asia with fewer fossil fuel driven vehicles and with more trees and greenery would have a number of co-benefits including public health.

Extreme events will have greater impact on human health, security, livelihood, and poverty sectors with different magnitude and types in Asia (high confidence) [24.4.6]. More frequent and intense heat-waves in Asia will increase mortality and morbidity in vulnerable groups. Increases in heavy rain and temperature will increase the risk of diarrheal diseases and malaria. Increases in flood and drought will exacerbate rural poverty in parts of Asia due to negative impacts on rice crop and increases in food prices and the cost of living.

There are regions within Asia that are not sufficiently represented in studies of observed climate change, in particular Central and West Asia [24.8]. Numerical data on trends in precipitation is hard to find compared to trends in temperature. Furthermore, research data on changes in extreme climate events does not cover most Asian regions. Studies of both observed and projected impacts on biodiversity, boreal forest dynamics, CO_2 fertilization of crops and plants, and urban settlements are limited. More trans-disciplinary research is needed on direct and indirect health effects from climate change impacts on air and water quality and water quantity in different parts of Asia. The vulnerability, impacts and adaptation of aggregated household welfare, livelihoods and poverty need to be adequately studied.

24.1. Introduction

Asia is defined here as the land and territories of 51 countries/regions (see Figure 24-1). It can be broadly divided into six sub-regions based on geographical position and coastal peripheries (see Table 24-1). These are (in alphabetical order) Central Asia (5 countries), East Asia (7 countries/regions), North Asia (2 countries), South Asia (8 countries), Southeast Asia (12 countries) and West Asia (17 countries). Asia has a diversity of social, cultural and economic characteristics. The population of Asia in 2011 was reported to be about 4,207 million, which is about 60% of the world population (UN, 2011). The population density is about 134 per square kilometer (PRB, 2012). The highest life expectancy at birth is 83 (Japan) and the lowest is 49 (Afghanistan). In 2009, the GDP per capita ranged from US$ 543 (Afghanistan) to US$ 45,903 (Japan) (World Bank, 2013). Almost half of the population in Asia lives below the poverty line, where their income is below US$ 1.25 per day by 2005 prices (World Bank, 2013).

[INSERT FIGURE 24-1 HERE
Figure 24-1: The land and territories of 51 countries/regions.]

[INSERT TABLE 24-1 HERE
Table 24-1: The 51 countries/regions in the six sub-regions of Asia.]

24.2. Major Conclusions from Previous Assessments

24.2.1. Climate Change Impacts

Climate change, variability and extreme events

Observed. Warming is strongest over the continental interiors of Asia, and warming in the period 1979 onwards was strongest over China in winter and eastern Asia in spring and autumn. [WG1 AR4 3.2.2.7]. From 1900 to 2005, precipitation increased significantly in northern and central Asia but declined in parts of southern Asia [WGI AR4 SPM]. A warming trend in daily temperature extremes was observed for much of Asia (medium confidence) [SREX 3.3.1]. No systematic spatially coherent trends in heavy precipitation have been found in most of Asia, except for a weak increase in the frequency of extreme precipitation that was observed in northern Mongolia (low to medium confidence) [SREX 3.3.2]. However, both positive and negative statistically significant trends have been found at sub-regional scales throughout Asia (low to medium confidence) [SREX 3.3.2]. A decreasing trend was observed in rainfall in the South Asian and East Asian monsoons, due to a rise in sea-surface temperature [SREX 3.4.1]. Coastal areas of Asia have reported that sea level rise has accelerated relative to the long-term average and is greater than the global average [WG2 AR4 10.3.1].

Future projections. Future projections show that warming will be least rapid in Southeast Asia, stronger over South Asia and East Asia, and greatest in the continental interior, with the most pronounced warming at high latitudes in North Asia [WG2 AR4 10.3.1]. Annual precipitation projections indicate an increase in most of Asia during this century [WG2 AR4 10.3.1]. An increase in heat waves is also projected for South Asia, East Asia, and Southeast Asia [WG2 AR4 10.3.1]. Future projections suggest that heavy precipitation will increase in West and South Asia, as well as the Asian monsoon region, notably in Bangladesh and in the Yangtze river basin [SREX 3.3.2], while projection results for the South Asian monsoon precipitation point to both increases and decreases in precipitation (low confidence) [SREX 3.4.1].

Climate change impacts

Observation. Changes in drought patterns have been reported for the monsoon regions of Asia with variations at the decadal time scale (low confidence) [SREX 3.5.1]. Studies in East Asia show increasing dryness in the second half of the 20th century (medium confidence) [SREX 3.5.1]. Flood observation results show that there is an upward trend in the annual flood maxima of the lower Yangtze, increasing likelihood for extreme floods in the Mekong river, and both upward and downward trends in four selected river basins of the northwestern Himalaya (low confidence) [SREX 3.5.2].

Projections. Global and regional studies project a higher likelihood of hydrological drought by the end of the century, with a substantial increase in the number of drought days in southern Asia from Indochina to southern China, while increases in drought are projected for inland China and central Eurasia [SREX 3.5.1]. Projections point to an increase in the risk of floods in most humid Asian monsoon regions (low confidence) [SREX 3.5.2].

24.2.2. Vulnerabilities and Adaptive Strategies

Vulnerable sectors. Crop yields in the past few decades have declined in many parts of Asia due to increasing water stress arising partly from increasing temperature, increasing frequency of El Niño events and reductions in the number of rainy days (medium confidence) [WG2 AR4 10.2.4.1]. Studies suggest that in the future as well substantial decreases are probable, not only in cereal production potential (medium confidence) [WG2 AR4 10.ES], but also in the production of livestock, fisheries, and aquaculture [WG2 AR4 10.4.1.1; WG2 AR4 10.4.1.3]. Most projections suggest that increasing urbanization and population in Asia could result in increased food demand and reduced food supply due to limited availability of cropland area and yield declines [WG2 AR4 10.4.1.4]. Food insecurity and loss of livelihood would be further exacerbated by the loss of cultivated land and nursery areas for fisheries by inundation and coastal erosion in tropical Asia [WG2 AR4 10.4.1.4]. Changes in the hydrological cycle

with corresponding changes in the water resources have been observed, with a noticeable regional variability, in all of Asia [WG2 AR4 10.2.4.2]. One of the most pressing environmental problems in South and Southeast Asia will be the expansion of areas under severe water stress as the number of people living under severe water stress is projected to increase substantially in absolute terms [WG2 AR4 10.4.2.3]. Oceanic, coastal, and other natural ecosystems have suffered degradation as a result of global warming, sea-level rise and changes in intensity and amount of precipitation [WG2 AR4 10.2.4.3; WG2 AR4 10.2.4.4]. Projections show that all coastal areas in Asia are facing an increasing range of stresses and shocks, the scale of which now pose a threat to the resilience of both human and environmental coastal systems, and could be additionally exacerbated by climate change [WG2 AR4 10.4.3.1]. Many plant and animal species are at risk of becoming extinct as a consequence of the combined effects of climate change and habitat fragmentation (medium confidence) [WG2 AR4 10.ES; WG2 AR4 10.2.4.5]. Central, East, South and Southeast Asia reported deaths and disorders from heat waves and outbreaks of infectious diseases linked to rising temperatures and rainfall variability, particularly in low-income areas with poor water and sanitation safety (medium confidence) [WG2 AR4 10.ES; WG2 AR4 10.2.4.6]. Substantial direct impacts on public health and livelihood can be expected also in the future due to possible increases in climate change related diseases, as well as heat stress [WG2 AR4 10.4.5]. Climate change is also expected to adversely affect the sustainable development capabilities of most Asian developing countries by aggravating pressure on natural resources and the environment, in addition to factors such as rapid urbanization, industrialization and economic development (high confidence) [WG2 AR4 10.ES ; WG2 AR4 10.7].

Vulnerable areas. Regions of South and Southeast Asia were reported as vulnerable to climate change, due to the exposure of their population to severe water stress [WG2 AR4 10.4.2.3]. Furthermore, the same regions are expected to experience higher endemic morbidity and mortality due to diarrheal disease related to climate change (high confidence) [WG2 AR4 10.ES; WG2 AR4, 10.4.5]. Increases in coastal water temperature would exacerbate the risk of cholera in South Asia (high confidence) [WG2 AR4 10.ES; WG2 AR4 10.4.5]. Crop yields in South and West Asia could decrease by a third by the middle of this century (medium confidence) [WG2 AR4 10.ES; WG2 AR4 10.4.1.1]. Glaciers on the Tibetan Plateau are projected to shrink at an accelerated pace, thus possibly increasing the number and intensity of glacial melt-related floods and leading to slope destabilization and a decrease in river flows as glaciers recede (medium confidence) [WG2 AR4 10.ES; WG2 AR4 10.4.2.1; WG2 AR4 10.2.4.2]. Projected sea-level rise would result in significant losses of coastal ecosystems, along with increased risk of flooding on the coasts of South and Southeast Asia (high confidence) [WG2 AR4 10.ES; WG2 AR4 10.4.3.1]. Sea-level rise and declining river runoff, coupled with extreme events such as flooding and intensifying storm surges, would have adverse impacts on human settlements, aquaculture industry and infrastructure of Asia's densely populated megadeltas (high confidence) [WG2 AR4 10.4.3.2; SREX 4.4.3]. Stability of wetlands, mangroves and coral reefs around Asia is likely to be increasingly threatened (high confidence) [WG2 AR4 10.ES; WG2 AR4 10.4.3.2; WG2 AR4, 10.6.1].

Adaptive strategies. Adaptive strategies for the agricultural sector that have been identified in AR4 are intended to increase adaptive capacity by modifying farming practices, improving crops and livestock through breeding, investing in new technologies and infrastructure, and making changes in management philosophy through education and the provision of climate change-related information [WG2 AR4 10.5.1]. In the water sector, dealing with water use inefficiency and the promotion of recycled water were found useful in many agricultural areas in Asia [WG2 AR4 10.5.2]. Along the coast, protection, such as dike heightening and strengthening, is considered to be important in responding to sea-level rise [WG2 AR4 10.5.3]. Most forests in Asia would benefit from comprehensive inter-sectoral programs that combine measures to control deforestation and forest degradation [WG2 AR4 10.5.4].

Implementation of monitoring and warning systems would be helpful in reducing the impacts of climate change on human health [WG2 AR4 10.5.5]. Effective adaptation and adaptive capacity in Asia, particularly in developing countries, will continue to be limited by several ecological, social and economic, technical and political constraints [WG2 AR4 10.5.7]. These constraints also include alterations of the physical environment, as well as the adaptive capacities of some ecosystems, spatial and temporal uncertainties associated with forecasts of regional climate, limited national capacities in climate monitoring and forecasting, and lack of coordination in the formulation of responses [WG2 AR4 10.5.7]. Countries of Asia facing serious domestic conflicts, pervasive poverty, hunger, epidemics, terrorism and other urgent and pressing concerns may not view climate change and the need to implement adaptation as immediate priorities [WG2 AR4 10.5.7]. Slow changes in the political and institutional landscape, and in the existing legal and institutional framework, remain inadequate to facilitate implementation of

comprehensive and integrated responses to climate change [WG2 AR4 10.5.7]. In order to address such constraints the following measures would be of use: improving access to high-quality information about the impacts of climate change; adaptation and vulnerability assessment by setting in place early warning systems and information distribution systems to enhance disaster preparedness; reducing the vulnerability of livelihoods and infrastructure to climate change; promoting good governance, including responsible policy and decision making; empowering communities and other local stakeholders so that they participate actively in vulnerability assessment and implementation of adaptation; and mainstreaming climate change into development planning at all scales, levels and sectors [WG2 AR4 10.5.7].

_____ START BOX 24-1 HERE _____

Box 24-1. What's New on Asia in AR5?

- Improved country coverage on observed and future impacts of climate change
- Increase in number of studies reflecting advances in assessment tools (e.g. more use of remote sensing and modelling of impacts); with an evaluation of detection and attribution where feasible.
- More conclusions now have confidence statements, while confidence levels have changed in both directions since AR4.
- Expanded coverage of issues; for example discussion on the Himalayas has been expanded to cover observed and projected changes as well as impacts [Box 3-2] including on tourism [10.6.2]; livelihood assets such as water and food [9.3.3.1; 13.3.1.1; 18.5.3; 19.6.3]; poverty [13.3.2.3.]; cultural erosion [12.3.2]; flood risks [18.3.1.1; 24.2.1]; health risks [24.4.1.2; 24.4.6.2] and forest distribution [24.4.2.2].

_____ END BOX 24-1 HERE _____

24.3. Observed and Projected Change

24.3.1. Observed Climate Trends and Variability

Temperature. In accordance with the findings of AR4, increasing trends in annual mean temperature at the country scale have been observed across most of the Asian region, including the Tibetan Plateau, during the 20th century, with the warming trend continuing into the new millennium (see Table 24-2). The contribution of the urban heat island effect to the temperature increase have also been pointed out (Fujibe, 2011; Ren, 2008). Despite a limited amount of information, a stronger upward trend is observed for winter mean temperatures, as compared to the summer means in East Asia, as well as in Bangladesh, Nepal, and over eastern Khengay and across the Khentey Mountains, Mongolia (Kim and Roh, 2010; Khattak *et al*., 2011, Schaefer and Domroes, 2009; Shahid, 2010). On the other hand, decreasing trends were observed for the summer diurnal temperature range in the northwestern part of Kashmir, India (Roy and Balling, 2005), and for the mean minimum temperature in Karachi, Pakistan (Sajjad *et al*., 2009).

[INSERT TABLE 24-2 HERE
Table 24-2: Summary of key observed past and present annual mean temperature trends in Asian countries/regions.]

Precipitation. Annual mean precipitation trends are characterized by strong variability, with both increasing and decreasing trends observed throughout Asia (see Table 24-3). In India, Japan, and Kazakhstan no clear national trend was observed, although on a subnational level both positive and negative trends were observed. Total summer precipitation shows an increasing trend in Southeast and Northwest China and a decreasing trend in Central China (Yao *et al*., 2008).

[INSERT TABLE 24-3 HERE
Table 24-3: Summary of key observed past and present annual mean precipitation trends in Asian countries/regions.]

24.3.2. Observed Changes in Extreme Climate Events

As summarized in 24.2.1, based on SREX, trends of extreme events have been observed throughout Asia and additional events have been recorded.

Temperature extremes. Warm days and nights are significantly increasing in such regions as West Asia, South Asia, Southeast Asian coasts and Northeastern Siberia. They are, in contrast, significantly decreasing in regions including Mongolia, North China, Afghanistan and Pakistan, and Malaysia (Fang *et al*., 2008). Extreme warm-month events have strong spatial dependence, with smaller variability over the Tibetan Plateau, the North China plain and coastal areas of South China, and larger variability over North China (Wan, 2009).

Heat waves. Trends in heat waves displayed noticeable regional variability. Regional wet heat waves are more frequent and intense in China (Ding and Qian, 2011).

Heavy precipitation. Regionally and sub-regionally varying trends have been observed in heavy precipitation over the Asian continent. The western part of Russia shows increases in heavy precipitation considerably with exceeding areas of decrease, in eastern part, speeds of the increase in heavy precipitation are lower and those of decrease, higher, than in Western part (Bogdanova *et al*., 2010). Heavy precipitation has mainly increased in West Japan and in autumn, although weak positive trends have been found in most other regions and seasons (Fujibe *et al*., 2006; Fujibe, 2008). The frequency of extreme rainfall has increased in Southeast China (Yao *et al*., 2008) and the frequency and intensity have increased in Korea (Im *et al*., 2008; Ho *et al*., 2003; Im *et al*., 2011). The intensity of extreme wet days has increased and the frequency of extreme wet days significant decreased in some parts of Peninsular Malaysia (Zin *et al*., 2010). Variability in the frequency and intensity of extreme rainfall during the monsoon season has been observed in India (Goswami *et al*., 2006; Rajeevan *et al*., 2008)

Dryness. Spatially varying trends in dryness, indicated by different measures (Consecutive Dry Days, Soil Moisture Anomalies, Palmer-Drought Severity Index) were observed within most Asian regions. Soil moisture droughts have become more severe, prolonged, and frequent during the past 57 years in China, especially northeastern and central China (Wang *et al*., 2011a)

Cyclones. Typhoon influence has increased in subtropical East Asia and considerably decreased over the South China Sea due to changes in the large-scale steering flow (tropospheric cooling in the last 20 years was suggested as cause) (Wu *et al*., 2005). Tropical cyclone frequency shows a decreasing trend over most parts of China, except at some locations in the low reaches of the Yangtze River (Ying *et al*., 2011). Duration of the most extreme winds, including tropical storms and typhoons, has been growing over Southeast Asian seas, mainly the South China Sea and the Philippine Sea (Rozynski *et al*., 2009). Frequency of typhoon passage has decreased significantly in the East China Sea and Philippine Sea in the 1980-2001 periods, relative to 1951-1979, and a continuous downward trend over the Philippine Sea has been observed. (Ho *et al*., 2004). Tropical cyclone frequency has decreased in the northwestern Pacific, while in the southeastern Pacific it increased until the early 1990s and then decreased moderately (Chen, 2009).

24.3.3. Socio-Economic Scenarios for Climate Modeling and Assessment of Impacts, Adaptation and Vulnerabilities

In the process of assessing climate change for the purposes of AR5, scenarios called Representative Concentration Pathways (RCPs) were developed, in which a wider range of potential future radiative forcing pathways were presented. Subsequently, socio-economic and climate scenarios have been developed in parallel by utilizing the RCPs [WG2 AR5 FOD 1.1.3; WG3 AR5 FOD 6.1.3]. The purpose of developing the four RCP scenarios was to compare climate change, climate change impacts, and emission pathways under different stabilization targets (Moss *et al*., 2010). Shared Socio-economic Pathways (SSPs) and Shared Climate Policy Assumptions (SPAs) have also been developed to provide scenario elements such as Economic Growth, Globalization, Distribution/ Equity, Environmental Ethics and Values, Institutions and Governance, Technological Change and Access, and Population and Demographics (Kriegler *et al*., 2012; van Vuuren *et al*., 2012). SSPs and SPAs are essential for assessment of

impacts, adaptation and vulnerabilities (IAVs) because Asian countries have a huge variety of current socio-economic conditions [24.1] and their future socio-economic situation could be varied under scenario assumptions. Many Asia-specific research projects have been conducted for assessing future socio-economic conditions in connection with the achievement of a low-carbon society under the constraints of climate change stabilization (e.g. Winyuchakrit *et al*., 2011; Akashi *et al*., 2012; Shukla *et al*., 2010). On the other hands, few IAV research studies including or focusing on Asia have been reported in which IAVs are discussed in relation to differences in climate change and future socio-economic conditions (Hasegawa *et al*., submitted)

24.3.4. Projected Climate Change

The projected changes for temperature and precipitation in Asia are summarized based on AR5 WG1 SOD (see Table 24-4 and Figure 24-2).

[INSERT TABLE 24-4 HERE
Table 24-4: Summary of projected changes for a variety of climate parameters [WG1 AR5 SOD Ch. 14.]

[INSERT FIGURE 24-2 HERE
Figure 24-2: Change in annual temperature and precipitation in Asia.]

24.4. Observed and Projected Impacts, Vulnerabilities, and Adaptation

The key obserced and future climate change impacts in Asia are summarized based on sub-section from 24.4.1 to 24.4.6 (see Tables 24-5 and 24-6).

[INSERT TABLE 24-5 HERE
Table 24-5: Summary of key observed past and present climate change impacts in Asia.]

[INSERT TABLE 24-6 HERE
Table 24-6: Summary of key future climate change impacts in Asia.]

24.4.1 Freshwater Resources

24.4.1.1. Sub-Regional Diversity

The water sector in Asia is significantly vulnerable to shifts in climate due to the dependence of its huge agricultural sector on precipitation, river runoff, and groundwater (see Table 24-5). Hence, adequate water supply is one of the major challenges in Asia, particularly Central Asia (Vorosmarty *et al*., 2010). Regional assessments of the environmental impact of the freshwater situation are greatly needed (Pfister *et al*., 2009). Growing demand for water is driven by soaring population, increasing urbanization, and thriving economic growth. Arid countries of the Middle East and Central Asia face major challenges in ensuring a freshwater supply, which will continue to decline with the decrease in precipitation, groundwater recharge and surface runoff (Kitoh *et al*., 2008). Mismanagement of water resources is increasing tension among five Central Asian states of the former Soviet Union – Kazakhstan, Kyrgyzstan, Turkmenistan, Uzbekistan, and Tajikistan (Lioubimtseva and Henebry, 2009; Siegfried *et al*., 2010).

24.4.1.2. Observed Impacts

Water availability has varied in most river catchments in China during the past several decades, detected with high confidence, but this can be attributed with low confidence to climate change rather than other human activities (see Table 24-5). No evidence shows significant changes in the Kherlen River Basin in Mongolia (Brutsaert and Sugita, 2008). The surface water resources of Central Asia are primarily generated in mountain glaciers. Increased runoff

from shrinkage of glaciers has been observed in the Himalayas (Zhang *et al*., 2011; case study box in Ch.3; case study 24.9.3) and Central Asian mountains due to increased temperature (high confidence in detection and attribution, Casassa, G., P. Lopez, *et al*., 2009; Shrestha and Aryal, 2011). Apart from water availability, climate change is correlated with surface water quality (medium confidence in detection and attribution, Prathumratana *et al*., 2008; Delpla *et al*., 2009; Huang *et al*., 2009 ; Park *et al*., 2010; Zhang *et al*., 2007), which may increase health risk (Tornqvist *et al*., 2011). It is also noticeable that groundwater quality is also related to climate change (Thakur and Ojha, 2010; Winkel *et al*., 2011; Fendorf *et al*., 2010; Gunawardhana and Kazama 2012). It has been suggested that the water crisis in Asian countries is partly caused by poor management (Biswas and Seetharam, 2008).

24.4.1.3. Projected Impacts

Projected impacts of future climate change (A1B scenario with 5 GCMs) on water availability in Asia, considering the future demand, differ substantially among river basins (Immerzeel *et al*., 2010). The water demand in most Asian countries is gradually increasing because of increases in population, irrigated agriculture (Lal, 2011) and growth in the industrial sectors. Tropical Asia will experience severe dry and wet spells that will reduce water supply reliability and increase chances of flooding. Even though precipitation in northern and temperate Asia is expected to increase overall (Park *et al*., 2010), socio-economic development will pose a challenge to freshwater resources. Projections (A2 scenario with multiple GCMs) suggest that throughout much of Russia a warmer climate would decrease water availability due to the increase in evaporation, but on the other hand precipitation would increase which tends to increase water availability (Alcamo *et al.,* 2007). In China, a projection (A2, PRECIS) suggests that there will be insufficient water for agriculture in the 2020s and 2040s due to the increases in water demand for non-agricultural uses, although positive trends in precipitation may occur in some areas (Xiong *et al*., 2010). In a study of the Mahanadi River Basin in India, the future water availability projection (A2, CGCM2) indicated an escalating trend in excess river runoff (runoff after meeting water demand), thereby increasing the future possibility of floods for the month of September, yet the outcomes for April indicate an accelerating water scarcity (Asokan and Dutta, 2008). In the Ganges, effects of climate change could become large enough to offset the large increases in demand in a +4ºC world, due to a projected large increase in rainfall (2ºC and 4ºC temperature increase from ensemble GCMs; Fung *et al*., 2011). Given the already very high level of water stress in many parts of Central Asia, projected temperature increases and precipitation decreases (SRES scenarios from IPCC AR4 23 models) in the western part of Kazakhstan, Uzbekistan, and Turkmenistan could exacerbate the problems of water shortage and distribution (Lioubimtseva and Henebry, 2009). Considering the dependence of Uzbekistan's economy on its irrigated agriculture, which is consuming more than 90% of the available water resources of the Amu Darya basin, climate change related impacts on river flows would also strongly affect the economy (Schlüter *et al*., 2010). Fresh water resources in coastal areas might be reduced over the next century in Asia, except for Southeast Asia, with the vulnerable areas including South India, the Bangladesh region and China (A2 scenario, HadCM3; Ranjan *et al*., 2009).

24.4.1.4. Vulnerabilities to Key Drivers

It is suggested that river discharge will be influenced by rainfall change and rapid melting of snow and frozen soil in the river catchment (Tachibana *et al*., 2008) associated with climate change (Jian *et al*., 2009). Snowfall and snow melting is estimated to be very sensitive to climate warming because the surface air temperatures in heavy snow regions in Monsoon Asia are near 0°C even during winter. The seasonal cycle of river runoff would be modified and affect water management in heavy snow regions in Asia (Ma *et al*., 2010; Im *et al*., 2010; Sato *et al*., 2012; Yamanaka *et al*., 2012). Water management in river basins needs to be coordinated among countries, for example water management in the Syr Darya river basin relates to Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan, Kazakhstan (Siegfried *et al*., 2010).

24.4.1.5. Adaptation Options

Asia is by far the largest user of irrigation water in terms of volume. During the second half of the 20th century, Asia has built many reservoirs and almost tripled its surface water withdrawals for irrigation. Reservoirs partly mitigate the seasonal differences and increase water availability for irrigation (Tyler and Fajber, 2009; Biemans *et al.*, 2011). However, they might not be able to continue the same supply because of a change in reservoir inflow due to the effects of climate and socioeconomic change. To adapt to the climate change impacts on water resources, many Asian countries apply water saving technologies in irrigation (Ngoundo *et al.*, 2007; Tischbein etal., 2011) and other consumptive purposes (Fleskens *et al.*, 2007), change to more drought-tolerant crops (Thomas, 2008; Zhao *et al.*, 2010), increase water supply (Sadoff and Muller, 2009), and improve management (Kranz *et al.*, 2010). In monsoonal Asia, development of water control systems has contributed to improved rice harvests (Hatcho *et al.*, 2010).

Four strategies (a new flood map, an early warning system, a relief program, and more community education) have been developed in the Sarawak River system in Malaysia to reduce the excessive flood loss (Mah *et al.*, 2011). Hazard mapping could help both decision-makers and local communities to understand the current situation and, through this, it would be possible to anticipate or assess the flexibility to adapt to future changes through proper planning and technical design. Examples include mapping in the Himalayan region (Eriksson *et al.*, 2009), risk mapping of slope failure in Japan (Ono *et al.*, 2011) and proposed investments in river regulation and storage in Nepal to control floods and to augment low-season flows in India and Bangladesh in the Ganges River Basin (Sadoff and Muller, 2009).

The equitable sharing of water and the drought-proofing of rural livelihoods will require an increasing physical capacity to store water (van der Zaag and Gupta, 2008). Moreover, policy processes in the current water management regime are strongly shaped by informal institutions and the lack of enforcement of formal regulations. The high degree of centralization of the management regime (Webster and McElwee, 2009) and the lack of vertical integration are possible explanations for the rather low adaptive capacity (Schlüter *et al.*, 2010). Legal aspects of water management also need to be considered in South Aisa (Uprety and Salman, 2011; D'Agostino and Sovacool, 2011).

24.4.2. Terrestrial and Inland Water Systems

24.4.2.1. Sub-Regional Diversity

Asia supports examples of all the major natural terrestrial ecosystem types, with the predominant types differing between sub-regions. North Asia is a region of tundra, boreal forests and grasslands, Central and West Asia are dominated by desert and semi-desert ecosystems, and the Tibetan Plateau is covered in a variety of largely treeless alpine ecosystems. These four sub-regions have relatively low human population densities in most areas, except for parts of Central and West Asia, and are still largely covered in natural ecosystems, although some of these have been extensively modified. In the three remaining sub-regions, in contrast, natural ecosystems have been completely replaced over large areas by human-dominated landscapes. The major natural ecosystems of East Asia included temperate deciduous and subtropical evergreen forests, giving way to boreal forest in the northeast and to grasslands and deserts in the west. South Asia and Southeast Asia were largely covered in tropical forests, with deciduous and semi-evergreen forests most extensive in South Asia and evergreen rain forests more important in Southeast Asia. South Asia also has extensive semi-desert areas in the west and northwest, and a variety of alpine ecosystems in the north, while Southeast Asia supports a small area of alpine vegetation and ice above the treeline in New Guinea. Asia includes several of the world's largest river systems (Indus, Ganga-Brahmaputra-Meghna, Irrawaddy, Mekong, Pearl [Zhu Jiang], Yangtze [Chang Jiang], Yellow [Huang He], Amur, Lena, Yenisei, Ob, Mamberamo, Fly, Sepik) with their associated deltas, as well as the world's deepest freshwater lake, Lake Baikal, the semi-saline Caspian Sea, and the saline and now greatly shrunken Aral Sea.

24.4.2.2. Observed Impacts

Temperatures have shown a largely consistent rise across Asia since 1970, but changes in precipitation have been complex and varied [WG1 AR5 SOD Ch. 14]. In general, observations of biological changes in terrestrial ecosystems consistent with the impacts of climate change are more common in the cold and/or arid north and west of the region, and at high altitudes, where rising temperature and, in some areas, increasing precipitation have relaxed constraints on the growth of plants and the distributions of both plants and animals. In contrast, there have been very few reports from the tropical lowlands of impacts and none that can be linked to recent climate change with high confidence. Many changes in inland water systems have also been reported, but the impacts of climate change have been difficult to disentangle from natural variability and a wide variety of other, concurrent, human impacts (Bates *et al*., 2008; Wang *et al*., 2011b; Zheng, 2011).

Phenology and growth rates. The most widely reported impacts attributed to the observed climate trends have been changes in the timing of life-history events in plants and animals. Combining information from species-level observations of plants, satellite measurements of 'greenness' (Normalized Difference Vegetation Index, NDVI) and modeling, Ma and Zhou (2012) conclude that plant growth in China has started on average 2.9 days per decade earlier since the early 1980s and that this is *likely* a response to spring warming. The shift was largest in forests and smallest in grasslands and shrublands, where changes in precipitation may be more important. Regional studies in northern and eastern China, and in Japan, using observational or satellite data, have shown similar general trends, with earlier greening in spring, delayed senescence in autumn, and thus a longer growing season, associated with rising temperatures, although the details vary between sites and species (Doi and Katano, 2008; Bai *et al*., 2010; Guo *et al*., 2010; Li and Zhou, 2010; Yu *et al*., 2010; Cai *et al*., 2012; Chen and Xu, 2012; Dai *et al*., 2013; Ogawa-Onishi and Berry, 2013). Earlier spring flowering associated with rising temperatures has also been recorded for a variety of tree species across temperate China and Japan (Doi, 2007; Doi and Katano, 2008; Wu *et al*., 2009; Bai *et al*., 2010; Fan *et al*., 2010; Fujisawa and Kobayashi, 2010; Ge *et al*., 2011; Dai *et al*.., 2013), with cherry trees in Kyoto now flowering earlier than they have at any time in the previous 1200 years (Primack *et al*., 2009). In temperate East Asia, these changes in plant phenology have been detected with high confidence and can be attributed to climate change with medium confidence. Changes in animal phenology have also been reported from China, Japan and South Korea, but their direction varies between species and locations, and the relationship with climate change is often unclear (Kusano and Inoue, 2008; Lee *et al*., 2011; Kobori *et al*., 2012; Ogawa-Onishi and Berry, 2013).

In the boreal forests of northern Asia, satellite data, validated with ground observations, shows a trend to earlier greening from 1982 to the 1990s, which is strongest in Central Siberia, followed by a slight delay in many areas (Delbart *et al*., 2008). On a continental scale, boreal forest leafing advanced by 3.9 days per decade for 1982-1999 and was earlier in the mid-1990s in Central Siberia than at any time since 1920. A general trend to earlier spring green-up from 1982 to 2006 is also evident from satellite NDVI data for the Hindu-Kush-Himalayan region, from Afghanistan to Myanmar, with the strongest temporal trends in the west (Panday and Ghimire, 2012). A more detailed study of the Himalayas over the same period found that the growing season had advanced by an average of 1.9 days per decade, with no change at the end of the season, in apparent response to a mean warming of 1.5 ºC (Shrestha *et al*., 2012). There was a great deal of spatial heterogeneity, with areas in the drier western Himalayas more likely to have negative correlations with spring temperatures and a positive response to rainfall. In the Trans-Himalayan region of Nepal, wetter areas followed regional trends, but semi-arid areas had a delayed and shortened growing season from 2000 to 2009, as a result of a decline and delay in snow cover (Paudel and Andersen, 2012). Patterns were heterogeneous for 1981-2008 in Central Asia, where temperatures are generally increasing and precipitation decreasing (Kariyeva *et al*., 2012). NDVI data showed an earlier start to the growing season in much of the region, but a substantially later start in desert and semi-desert areas in Turkmenistan and southern Uzbekistan. On the Tibetan Plateau, the start of spring growth in meadows and steppe advanced until the mid-1990s, after which it retreated, so there was no overall significant trend over the period 1982-2006, despite continued warming and increases in spring NDVI (Yu *et al*., 2012). These trends may be related to unfulfilled winter chilling requirements of the grasses. Herbarium records from Tibet show earlier flowering by 5 days per decade for a set of 41 species over the period 1961-2000 (Li *et al*., 2013).

Recent changes in the growth rates of plants have also been widely reported and, where long records are available from tree rings, these changes can be linked to recent climate change (high confidence in detection, medium confidence in attribution to climate change). A reconstruction of summer temperatures for East Asia north of 23ºN for the period 800-1989, based on a network of tree-ring data, suggests that recent instrumental temperatures have exceeded those during past warm periods of similar length, but this difference was not statistically significant (Cook *et al*., 2013). In areas where temperature limits tree growth, recent decades have generally seen an increase in growth rates correlated with rising temperatures (e.g., Duan *et al*., 2010; Sano *et al*., 2010; Shishov and Vaganov, 2010; Borgaonkar *et al*., 2011; Xu *et al*., 2011; Li *et al*., 2012; Cao *et al*., 2012; Chen *et al*., 2012 a, b, c, d; Chen *et al*., 2013), while in areas where drought limits growth, there have been increases (Yang *et al*., 2010) or decreases (Dulamsuren *et al*., 2010a, 2011; Kang *et al*., 2012; Wu *et al*., 2012; Lu *et al*., 2013) in growth reflecting decreasing or increasing aridity. In the boreal forest zone, changes in tree growth varied between species and locations, despite consistent warming, with suggested reasons for decreased growth including drought stress, pollution, declining solar radiation, and direct temperature stress (Lloyd and Bunn, 2007; Goetz *et al*., 2011).

Where ground-based data is absent, satellite NDVI data can be used as a proxy for changes in vegetation density and photosynthetic capacity, which in turn reflect plant growth, although there are problems with both the NDVI data and its interpretation (Zhao *et al*., 2012; Xu *et al*., 2012). For Asia as a whole, the spatial pattern of trends in NDVI for 1988-2010 largely matches data on microwave-based surface soil moisture, with a greening trend dominant except where water is limiting (Dorigo *et al*., 2012). Changes in NDVI at high latitudes (>60ºN) in 1982-2008 show considerable spatial and temporal variability, despite a consistent warming trend, reflecting variations in water availability as well as non-climatic factors (Jeong *et al*., 2013). Arctic tundra generally showed increased greening between 1982 and 2005, while boreal forests were more variable, in agreement with tree-ring data (Goetz *et al*., 2011; de Jong *et al*., 2012). An overall greening trend for 2000-2011 north of the boreal forest correlated with increasing summer warmth and, to a lesser extent, summer ice retreat (Dutrieux *et al*., 2012). In China, NDVI trends have varied in space and between time periods, reflecting the varying balance between the positive impacts of rising temperature and negative impacts of increasing drought stress (Peng *et al*., 2011; Sun *et al*., 2012). In Central Asia, where NDVI is most sensitive to changes in precipitation (Gessner *et al*., 2013), there was a complex and heterogeneous pattern for 1982-2009, with an initial regional greening trend stalled or reversed in some areas and time periods (Mohammat *et al*., 2013). In the desert boundary regions (precipitation 200 mm yr^{-1}) of South, Central and Northern Asia, NDVI data showed that the bare soil area declined in 1982-1998, but expanded in 1998-2008 (Jeong *et al*., 2011). In the northern deserts (Karakum, Taklimakan and Gobi), these changes were related to an initial increase then decline in precipitation, while temperature continued to rise, while in the southern deserts (Lut and Thar) non-climatic factors appear to be more important. The steppe region of northern Kazakhstan has also shown an overall browning (lower NDVI) trend in 1982-2008, linked to declining precipitation (De Jong *et al*., 2012).

The carbon budget of all terrestrial ecosystems in East Asia (China, Mongolia, North and South Korea, Japan) from 1990 to 2009 was estimated using a combination of inventory and satellite-based data, ecosystem modeling (using 10 models), and atmospheric inversion models (Piao *et al*., 2012). Although there are large uncertainties in each approach, the results together suggest that the region as a whole was a significant carbon sink over this period (average -0.294 Pg C yr^{-1}), with the negative impacts of drought in some areas largely overcome by the positive impact of CO_2 fertilization.

The distributions of species and biomes. Also widely reported are changes in the distributions of plant and animal species: generally upwards in elevation (e.g. Soja *et al*., 2007; Round and Gale, 2008; Bickford *et al*., 2010; Kharuk *et al*., 2010 a, b, e; Moiseev *et al*., 2010; Chen *et al*., 2011; Jump *et al*., 2012) or polewards (e.g. Tougou *et al*., 2009; Ogawa-Onishi and Berry, 2013) in response to recent warming (high confidence in detection, medium confidence in attribution to climate change). Movements of dominant plant species can eventually lead to changes in the distributions of major vegetation types (biomes). Evidence for biome shifts has so far been reported only from the north of the region and at high altitudes, where it involves trees invading treeless tundra, steppe or alpine meadows, or the invasion of the forest understory by species from adjacent biomes (Soja *et al*., 2007; Kharuk *et al*., 2006; Bai *et al*., 2011; Singh *et al*., 2012; Wang and Liu, 2012; Ogawa-Onishi and Berry, 2013). In Uttarakhand, in the Indian Himalayas, the treeline has moved upwards into the alpine zone by an average of 388 m between the 1970s and 2006 (Singh *et al*., 2012).

Larch-dominated forest occupies about half the area of Siberia. Invasion of dark needle conifers (DNC, e.g. Siberian pine, spruce and fir) and birch into the larch habitat over the last three decades has been observed, correlating with winter temperature increases (Kharuk *et al.*, 2010c). Siberian pine and spruce have high invasion potential both along the margin and in the centre of the larch-dominated zone. The process is wildfire dependant. On the western and southern margins of this zone, DNC regeneration has formed a second layer in the forest canopy, which could eventually replace the larch in the overstorey. In mixed stands, both larch and fir growth have increased over time, but the fir growth increase has been larger which may presage a shift in competitive balance between these species. Overall, it is *likely* that prevalence of evergreen conifers in areas currently dominated by deciduous larch species is increasing (Kharuk *et al.*, 2010c, d; Osawa *et al.*, 2010; Lloyd *et al.*, 2011). At the same time, climate change has driven larch stand crown closure, and larch invasion into tundra at a rate of 3–10 m/year was observed in the northern forest-tundra ecotone in Siberia in the last three decades of the 20th century (Kharuk *et al.*, 2006). Shrub expansion in arctic tundra as result of an increase in shrub growth, infilling of existing patches and the shrub line advancing into tundra has also been observed in the forest-tundra ecotone of Northern Asia (Myers-Smith *et al.*, 2011; Blok *et al.*, 2011; WG2 AR5 28.2.3.1.). Shrub growth is often strongly correlated with growing season temperatures, but is also influenced by fire, permafrost thaw and herbivory. Shrub and tree invasion of alpine meadows has also been reported in NW Yunnan, on the southeast edge of the Qinghai-Tibetan Plateau, between 1990 and 2009, and partly attributed to increasing temperatures and decreasing snow cover (Baker and Mosely, 2007; Brandt *et al.*, 2013).

In northern Asia, the position of the ecotone between boreal forest and tundra is controlled largely by air temperature during the growing season and annual precipitation, but forest fires can also catalyze change (Soja *et al.*, 2007). In contrast, soil moisture and light are the main factors governing the forest-steppe ecotone, although competition between trees and grasses, as well as fires, are also important (Soja *et al.*, 2007; Zeng *et al.*, 2008; Dulamsuren *et al.*, 2010 a, b; Eichler *et al.*, 2011). This ecotone in the western Khentey Mountains, northern Mongolia, has experienced a significant increase in summer temperature and decrease in summer precipitation since 1961. Siberian larch tree-ring analysis shows a strongly decreasing annual increment since the 1940s (Dulamsuren *et al.*, 2010a). Regeneration of larch decreased as well and is now virtually lacking in this forest. Studies on a wider scale show a great deal of heterogeneity in the responses of Mongolian taiga forests to recent climate changes, but declines in larch growth and regeneration are more widespread than the opposite trend (Dulamsuren *et al.*, 2010b).

Permafrost and glaciers. Degradation of permafrost, including reductions in area and increased thickness of the active layer, has been reported from parts of Siberia, Central Asia, and the Tibetan Plateau (Romanovsky *et al.*, 2010; Wu and Zhang, 2010; Zhao *et al.*, 2010; Yang *et al.*, 2013) (*high confidence*). Russia contains more permafrost than any other country: more than half of the Russian part of Northern Asia lies in permafrost zones, which constitutes a significant portion of the Northern Hemisphere permafrost area (FNCRF, 2010). Monitoring in most of the permafrost observatories in Asian Russia shows substantial warming of permafrost during the last 20 to 30 years (Romanovsky *et al.*, 2008, with supplement; 2010). Typical magnitude of warming varied from 0.5 to 2°C for different locations at the depth of zero annual amplitude. The main warming occurred between the 1970s and 1990s, with no significant warming after 2000. However, since 2007-2008 warming has resumed at many locations predominantly near the Arctic coasts. In Northwest Siberia, new closed taliks (areas of unfrozen ground) and an increase in the depth of preexisting taliks have been observed during last 20 to 30 years. Permafrost formed during the Little Ice Age is thawing at many locations and Late Holocene permafrost has begun to thaw at some undisturbed locations in northwest Siberia. Permafrost thawing is most noticeable within the discontinuous permafrost domain in Northern Asia, while in the continuous permafrost zone it is starting to thaw at some limited locations. As a consequence, the boundary between continuous and discontinuous permafrost zones is moving northward (Romanovsky *et al.*, 2008, with supplement; 2010). Over many thousands of years, the soil layer and bogs in the permafrost zone of Northern Asia have been accumulating huge amounts of organic matter. As permafrost thaws, reinforcement of the greenhouse effect is possible due to growing emissions of greenhouse gases [WG2 AR5 FOD 4.3.4.4.; WG2 AR5 FOD 19.3.5.].

The Qinghai-Tibet Plateau (QTP) and Central Asian region, including parts of Southern Siberia, Mongolia, Western China, Kazakhstan, and adjacent countries/regions, represent the largest area underlain by mountain permafrost in the world. Ongoing monitoring at numerous sites across the QTP regions over the past several decades has revealed

significant permafrost degradation caused by climate warming and human activities such as deforestation, forest fire, road construction and grazing: areas of permafrost are shrinking, the depth of the active layer is increasing, the lower limit of permafrost is rising, and the seasonal frost depth is thinning (Zhao *et al*., 2010; Li *et al*., 2008). The lower altitudinal limit of permafrost has moved up by 25 m in the north during the last 30 years and between 50 and 80 m in the south over the last 20 years in accord with long-term temperature measurements. Ground temperature at a depth of 6 m in 2001 has been higher by about 0.1-0.3°C than in 1996 according to data taken from seven natural sites on the Plateau (Cheng and Wu, 2007; Li *et al*., 2008). Over the period from 1995 to 2007, the mean rate of increase of the active layer thickness (ALT) was 7.5 cm/year (Wu and Zhang, 2010). Ground temperatures at the bottom of the active layer warmed on average by 0.06°C/year over the past decade (Zhao *et al*., 2010). In the alpine headwater regions of the Yangtze and Yellow Rivers, rising temperatures and permafrost degradation have resulted in lower lake levels, drying swamps and shrinking grasslands (Cheng and Wu, 2007; Wang *et al*., 2011c).

In the Kazakh part of Tien Shan Mountains, the increase in permafrost temperature during 1974-2009 at depths of 14-25 m varied from 0.3°C to 0.6°C. The average active layer thickness (ALT) increased by 23% in comparison to the early 1970s. In the eastern Tien Shan Mountains, in the headwaters of the Urumqi River, China, significant permafrost warming took place as the air temperature increased (Marchenko *et al*., 2007; Zhao *et al*., 2010). In Mongolia, mean annual ground temperature at 10-15 m depth over the past 10-40 years increased on average by 0.02-0.03°C/year in the Hovsgol Mountain region, and by 0.01-0.02°C/year in the Hangai and Hentei Mountain regions. During the past 15–20 years permafrost warming was greater than during the previous 15-20 years (1970s-1980s). The average rate of increase in mean annual ground temperature in Mongolia was about 0.15°C/decade (Sharkhuu *et al*., 2008; Zhao *et al*., 2010).

Mountain glaciers occur across Asia from the Arctic to the tropics [WG1 AR5 SOD Ch. 4]. Those in the polar section of the Ural Mountains are small (< 1km^2) and in total lost 20-30% of their mass in 1953-1981, with the main change in 1953-1963 and intensive degradation resuming since 1990 (Anisimov *et al*., 2008). Those in the Kodar Mountains of Southeast Siberia are also small (< 2 km^2) and the exposed ice area declined by c. 44% between ca. 1963 and 2010, with 40% loss since 1995, coinciding with a strong warming trend in June-August temperatures initiated in the 1980s (Stokes *et al*., 2013). In Northeast Siberia, the Suntar Khayata Range glaciers lost 19.3% of their area between the middle of the 20th century and 2003 and the Chersky Range glaciers lost 28 % in 1970-2003 (Ananicheva *et al*., 2005, 2006). Changes in the Kamchatka glaciers are driven by both temperature increase and volcano activity, with the area of some glaciers decreasing, while others increased because they are covered by ash and clinker (Anisimov *et al*., 2008). Glaciers of Georgia and Azerbaijan on the southern macroslope of the Greater Caucasus Range decreased in area by 31.2% in 1895-2000 (Anisimov *et al*., 2008). Yao *et al*. (2012) estimated that reduction in total area for glaciers on Tibetan Plateau and the surrounding areas during the past three decades, from the 1970s to 2000s, was c. 9%. In Papua, western Indonesia, the tropical mountain glaciers on Puncak Jaya have retreated rapidly since 1972, with rising temperatures thought to be the major factor (Prentice and Glidden, 2010; WG1, Ch. 4, AR5 SOD). Central Asian and Altai-Sayan glaciers are considered in more detail in the case study [24.9.3] and the Himalayan glaciers are considered in section 24.4.1 and in WG1 AR5 SOD Ch. 4.

24.4.2.3. Projected Impacts

The projected impacts in the literature assessed here include extrapolations from the observed trends, inferences from experiments, and projections from a variety of modeling approaches, based on projected climate change and projections for other factors, including carbon dioxide levels and land-use changes.

Phenology and growth rates. If air temperatures continue to rise, current trends towards an earlier spring and longer growing season in temperate and boreal forest areas are expected to continue, although photoperiod or chilling requirements may reduce the response in some plant species (Richardson *et al*., 2013). Changes in the timing and amount of precipitation will be at least as important as warming for semi-arid and arid ecosystems, making growth and phenological responses harder to predict, as shown by the varied responses of different plant species to experimental warming in the northern Mongolian steppe (Liancourt *et al*., 2012). The phenological drivers for tropical forests are not yet understood.

Distributions of species and biomes. The current distribution of vegetation across the region is controlled primarily by climate (particularly temperature, rainfall and snowfall, and their seasonality), modified over large areas by soils, permafrost, topography, and a variety of human impacts. In the longer term, therefore, climate change is expected to change this distribution (e.g. Wang, 2013). However, the rate at which this change in vegetation is realized will be constrained by many factors, including seed dispersal, competition from established plants, rates of soil development, and habitat fragmentation. Atmospheric CO_2 concentrations are an additional factor, with rising concentrations increasingly favoring C3 over C4 plants, and thus an increase in woody vegetation at the expense of grassland (Higgins and Scheiter, 2012; Wang, 2013).

Climate projections for Asia strongly suggest that the warming trend will continue, but projections for precipitation are still uncertain [WG1 AR5 SOD Ch. 14]. In Northern Asia, these changes in climate will lead to large and relatively predictable changes in the distribution of potential natural ecosystems (Ni, 2011; Tchebakova *et al*., 2011; Insarov *et al*., 2012), although the transitional stages will be less predictable. If current climate projections are correct, it is *likely* that the boreal forest will expand northward and eastward, and the tundra area will decrease, during the 21st century (Golubyatnikov and Denisenko, 2007; Korzukhin and Tcelniker, 2010; Lucht *et al*., 2006; Sitch *et al*., 2008; Tchebakova *et al*., 2010; Woodward and Lomas, 2004). However, for a shorter time horizon, some forest retreat and tundra advance by 2020 in Central Siberia have been projected (Tchebakova *et al*., 2011). Because models vary in accordance with their structure as well as biome classifications, climatic projections, CO_2 level and other characteristics used as inputs, the magnitude of the forest expansion varies greatly across models: Tchebakova *et al*. (2010) and Lucht *et al*. (2006) project that 93-100% of tundra area will be covered by boreal forest at the end of 21st century, Kaplan and New (2006) predict a 42% reduction in tundra area between 2026 and 2060, whereas Golubyatnikov and Denisenko (2007) estimate that 97% of tundra will remain unaltered by the mid-21st century.

The combination of boreal forest expansion and the continued invasion of the existing larch-dominated forest by dark-needle conifers could lead to a situation where larch reaches the Arctic shore, as has happened previously in the Holocene, whereas the traditional area of larch dominance will turn into mixed taiga forest (Kharuk, 2006, 2010c). Both replacement of summer-green conifers (larch) with evergreen conifers (DNC) and expansion of boreal forest and shrubs into regions now occupied by tundra decrease albedo. This change would cause heating of the atmosphere, a response that, in its turn could possibly accelerate the replacement of larch by DNC and of tundra by boreal forest (McGuire *et al*., 2007; Kharuk *et al*., 2006, 2010d). Energy budget feedback to the regional summer climate from the tundra to forest transition is estimated at 5.0 Wm^{-2} (McGuire *et al*., 2007). Overall there is a risk that future climate and environmental change, along with fire and permafrost degradation, could change some Siberian ecosystems, particularly disturbed forests and ecosystems on permafrost, from carbon sinks to sources of both CO_2 and CH_4 (Shvidenko *et al*., 2013).

The direction and rate of change in the extent of steppe vegetation is less clear, in part because of uncertainty in precipitation trends. One projection is that steppe area will increase by 27% for the decade beginning in 2090 (Tchebakova *et al*., 2010) while another is that it will decrease by up to 65% for late 2030s–early 2050s (Golubyatnikov and Denisenko, 2007). Reasons for the differences between these estimates include different projection horizons and vegetation classifications used. Increasing aridity may expand the deserts of northern China, and push the steppe to the northeast (Zhang *et al*., 2011), while a retreat of the southern limit of the taiga would expand the steppe area in the north (Dulamsuren *et al*., 2010b).

The forest regions of East Asia are expected to remain forested, but climates suitable for evergreen forests will expand north into the deciduous forest zone and the potential distribution of tropical forests will expand along China's southern coast (Choi *et al*., 2011; Wang, 2013). As observed elsewhere in the world, however, vegetation changes within lowland forest regions are expected to lag behind climate change by decades or even centuries, as fragmentation limits seed dispersal and long-lived forest dominants persist (e.g., Bertrand *et al*., 2011; Zhu *et al*., 2012). For example, climate models predict a large increase in the potential habitat for the evergreen broad-leaved tree species *Quercus acuta* in Japan, but short-distance seed dispersal by rodents will limit the ability of this species to occupy new areas (Nakao *et al*., 2011). On the Tibetan Plateau, multiple vegetation and climate models suggest that alpine vegetation will be largely replaced by forest and shrubland, with tundra and steppe retreating to the north of the plateau (Liang *et al*., 2012; Wang, 2013). In drier parts of the plateau, permafrost degradation will favor

plants that are tolerant of water stress (Cheng and Wu, 2007; Yang *et al*., 2013). The same models suggest that a large area of desert will persist in northwest China (Wang, 2013). Impacts in Central and West Asia will depend critically on the changes in precipitation, which are still highly uncertain. Projections for China from an atmospheric-vegetation interaction model under the SRES B2 scenario suggest that the arid northwest of the country is the most vulnerable ecoregion, with severe damage to desert ecosystems possible (Wu *et al*., 2010).

In the tropics and subtropics (<30ºN), many areas, including much of the Arabian Peninsula, India, southeastern China, and Southeast Asia, are expected to have climates by 2080 that do not occur anywhere on Earth at present (García- López and Allué, 2012), making predictions particularly difficult. In India, a dynamic vegetation model (IBIS) was combined with climate projections for 2100 (HadRM3 model, A2 and B2 scenarios) to produce projections for forest areas (Chaturvedi *et al*., 2011). More than a third of forest grids were projected to change forest type, with most changes from deciduous to evergreen forest in response to increasing rainfall, although fragmentation, loss of seed dispersal agents, and other human pressures are expected to slow these changes. The forests of the upper Himalayas, parts of Central India, northern Western Ghats and Eastern Ghats, appear to be most vulnerable to climate change. In the equatorial tropics, the relatively small annual temperature range means that by 2100 many lowland habitats are likely to experience temperatures every day that are outside the current range of extremes (Beaumont *et al*., 2010). The potential impacts of these novel climatic conditions are largely unknown (Corlett, 2011). If the frequency and severity of droughts increases, this is *likely* to interact with forest fragmentation and logging to increase fire risk (Daniau *et al*., 2012) and could also increase the risk of drought-induced tree mortality (Kumagai and Porporato, 2012).

An increasing number of studies have projected impacts on animals using a variety of modeling techniques. Hughes *et al*. (2012) projected the effects of both climatic (A2 and B1 scenarios) and vegetation changes on the distribution and diversity of bats in SE Asia. All projections predicted widespread declines in local bat species richness, northward range shifts for many species, and large reductions in the distribution of most species. Projections for the potential ranges of 63 species of galliform birds (pheasants, partridges and their relatives) in China (A2 scenario, 2071-2100) showed large (>50%), mostly northward, range shifts for 29 species (Li *et al*., 2010), while projections for the 13 species of nuthatches (Sittidae) in Asia (A2 and B2 scenarios, 2040-2069) found that most ranges would retract along their southern fringes and at lower elevations, with the largest range contractions in SE Asia and peninsular India (Menon *et al*., 2009). Projections for 17 endemic bird species in Taiwan (A2 and B2 scenarios, 5 GCMs) suggested 15 species would decrease their area of distribution by 2100 because of a shift to higher elevations, while two species from relatively low altitudes would increase (Ko *et al*., 2012). Projections for the distributions of 161 butterfly species in Thailand (A2 and B2 scenarios, 2070-2099) suggested that species richness within currently protected areas will decline c. 30%, but that these areas will continue to include a similar proportion of the highest priority sites for conservation (Klorvuttimontara *et al*., 2011). Projections for three dominant bamboo species in the Qinling Mountains, China (A2 and B2 scenarios, four GCMs) suggest substantial reductions in their ranges by 2100, with potentially adverse consequences for the giant pandas for which they comprise almost the entire current diet (Tuanmu *et al*., 2012). Projections for vegetation cover in the range of the threatened Yunnan snub-nosed monkey in southwest China in 2050 and 2100 (A1B scenario) suggest an increased area of the most suitable habitat, but greater fragmentation (Wong *et al*., 2013). Projections for snow leopard habitat in the Himalayas (15 GCMs, downscaled, B1, A1B and A2 scenarios) suggest this may contract by around 30% as forests move upslope and replace the open habitats this species needs (Forrest *et al*., 2012).

Permafrost. In the Northern Hemisphere as a whole, a 20-90% decrease in permafrost area and a 50-300 cm increase in active layer thickness (ALT) driven by surface warming is projected for 2100 by different models under SRES A1B, A2, B1 scenarios (Schaefer *et al*., 2011). The wide range of permafrost degradation projections may be result of different scenarios used, intensity of land atmosphere feedbacks and of difference in model internal structures. In Asia, it is *likely* that permafrost degradation during the 21st century will spread from the southern and low-altitude margins, advancing northwards and upwards as numerous models predict, but rates of change vary greatly between different model projections (Cheng and Wu, 2007; Riseborough *et al*., 2008; Romanovsky *et al*., 2008, with supplement; Anisimov, 2009; Eliseev *et al*., 2009; Nadyozhina *et al*., 2010; Schaefer *et al*., 2011; Wei *et al*., 2011). The spatially distributed permafrost model (Sazonova and Romanovsky, 2003) has been applied to the entire permafrost domain of Northern Eurasia, Central Asia and the QTP (Romanovsky *et al*., 2008, with supplement). If air temperatures continues to increase in accordance with the MIT 2D climate model output for the

21st century (Sokolov and Stone 1998), that is 2.2°C warming by 2031-50 and 4.7°C by 2080-2099 compared with 1981-2000 (Romanovsky *et al.*, 2008, with supplement), models show that permafrost that is presently discontinuous with temperatures between 0 and -2.5° C will cross the threshold by the end of 21st century and will be thawing actively. The most intense permafrost degradation in Russia is projected for Northwest Siberia. According to this model, the Late Holocene permafrost will be actively thawing everywhere except for the south of East Siberia and the Far East of Russia by the middle of 21st century. Almost all Late Holocene permafrost will be thawing, and some Late Pleistocene permafrost will begin to thaw in Siberia by the end of 21st century (Romanovsky *et al.*, 2008, with supplement). Near-surface permafrost is expected to remain only in Central and Eastern Siberia and in part of Tibet in the late 21st century. Depths of seasonal thaw are projected to exceed 1 m (2 m) in the late 21th century under the SRES B1 (A1B or A2) scenario in these regions (Eliseev *et al.*, 2009).

On the Qinghai-Tibet Plateau (QTP) and in northeastern China, substantial retreat of permafrost is expected during the 21st century due to the combined influence of climatic warming and increasing anthropogenic activities. No significant change will take place in permafrost conditions on the QTP over the next 20 to 50 years, but more than half of the permafrost in the southern and eastern parts of the plateau may become relict and/or even disappear by 2100 according to modeling results (Cheng and Wu, 2007). The result of permafrost degradation can dry the ground surface, and desertification may become an important environmental issue for the QTP (Cheng and Wu, 2007). In northeastern China, the southern limit of permafrost is expected to shift northwards, the total permafrost area to shrink, and the area of unstable permafrost to expand, with adverse consequences for associated wetlands and forests (Sun *et al.*, 2011; Wei *et al.*, 2011).

Inland Waters. Climate change impacts on inland waters will continue to interact over most of Asia with a wide range of other human impacts, including dam construction, pollution, and catchment land-use changes (see also Chapter 3, this volume). Increases in water temperature will be the most pervasive impact of climate change on both living organisms and a wide range of temperature-dependent ecological, chemical, and physical processes (Hamilton, 2010; Dudgeon, 2011, 2012). Coldwater fish will be threatened as rising water temperatures make much of their current habitat unsuitable (Yu *et al.*, 2013). The other major impact of climate change is expected to be on flow regimes in running waters and consequently on riverine habitats and species that are sensitive to flow extremes (droughts and floods) [see Box CC-RF: Freshwater ecosystems and altered river flows]. However, in the Mekong River, planned hydropower reservoirs are expected to have a larger impact on flow regimes than climate change (Lauri *et al.*, 2012). Regionally threatened natural habitats that depend on seasonal inundation, including floodplain grasslands and freshwater swamp forests, will be particularly vulnerable (Maxwell, 2009; Bezuijen, 2011). In Cambodia, the unique and hugely productive Tonle Sap Lake floodplain depends on an annual flood pulse from the Mekong River (Lamberts and Koponen, 2008; Arias *et al.*, 2012). Changes in river flow, in turn, have a direct impact on the freshwater to saltwater gradient where the river meets the sea, with reduced dry season flows combining with sea-level rise to increase saltwater intrusion in deltas (Hamilton, 2010; Dudgeon, 2012), although non-climatic human impacts will probably continue to dominate in most Asian estuaries (Syvitski *et al.*, 2009). Lakes will also be affected by climate change, but in most of Asia it is very difficult to disentangle the impacts of water pollution, hydro-engineering and climate change (Battarbee *et al.*, 2012). The ecology of China's largest freshwater body, Lake Poyang, is sensitive to the hydrological regime, which is potentially influenced by both engineering projects and climate change (Ye *et al.*, 2011; Zhang *et al.*, 2012). The unique ecosystem of Lake Baikal is expected to be impacted most by changes in ice duration and transparency, followed by water temperature and wind mixing (Moore *et al.*, 2009). Recent long-term trends towards earlier ice break-up, later freeze-up, and decreasing duration and thickness of ice cover, in close correspondence with rising air temperatures, are expected to continue in Arctic lakes and rivers, with unknown implications for freshwater and riparian ecosystems (Prowse *et al.*, 2011).

Thresholds and irreversible changes. Specific thresholds for terrestrial and inland water systems have not yet been identified. Studies of future climate change impacts on terrestrial ecosystems in China under the SRES B2 scenario suggest that moderate to severe impacts will increase significantly when temperatures increase by more than 2°C, but do not suggest a sharp threshold (Wu *et al.*, 2010). Species extinctions are the most likely irreversible change, with species that are unable to track climate change as a resulted of limited dispersal ability, habitat fragmentation, or non-climatic constraints, such as specialized soil requirements, most vulnerable (Heller and Zavaleta, 2009).

24.4.2.4. Vulnerabilities to Key Drivers

Changes in temperature are the most robust predictions and the most pervasive climate impact. Adverse impacts from rising temperature are *likely* in the wetter areas of north Asia and at high altitudes, with permafrost melting impacting ecosystems across large areas (Cheng and Wu, 2007; Tchebakova *et al*., 2011), but the impacts of higher temperatures in the tropical and subtropical lowlands are still unclear (Corlett, 2011). The biodiversity of isolated tropical, subtropical, and warm-temperate mountains may be most vulnerable to warming, because many species already have small geographical ranges that will shrink further in a warming climate (Liu *et al*., 2010; Chou *et al*., 2011; La Sorte and Jetz, 2011; Noroozi *et al*., 2011; Peh *et al*., 2011; Jump *et al*., 2012; Tanaka *et al*., 2012a). Many freshwater habitats are similarly isolated and their restricted-range species may be equally vulnerable (Dudgeon, 2012). Freshwater systems are also potentially vulnerable to increases in the frequency and intensity of extreme rainfall events (droughts or floods), even if average conditions are unchanged (Hamilton, 2010).

For much of Asia, increases in aridity, as a result of declining rainfall and/or rising temperatures, are the key concern. Because aridity is projected to increase in the northern Mongolian forest belt during the 21st century (Sato *et al*., 2007), the larch covered area will *likely* be reduced (Dulamsuren *et al*., 2010a). This will have far-reaching consequences for Mongolia's biodiversity and capacity to store water and carbon. It is likely it will also have significant socioeconomic consequences because the economy depends on the sustainable exploitation of natural resources. Even where mean rainfall remains adequate, any increase in drought frequency and/or severity will increase vulnerability to human-caused fires. The frequency and scale of both natural and manmade fires have recently increased in the tundra and taiga-tundra zones, as a result of warming, especially summer droughts (Kumpula *et al*., 2011; Nuttall 2005; Walker *et al*., 2011). If droughts intensify in the tropical lowlands of SE Asia, then the synergies between warmth, drought, logging, forest fragmentation and fire (Daniau *et al*., 2012), which may be further acerbated by feedbacks between deforestation, smoke aerosols and reduced regional rainfall (Aragão, 2012; Tosca *et al*., 2012), could greatly increase the vulnerability of fragmented forest landscapes to both fire and climate change.

24.4.2.5. Adaptation Options

The capacity of natural ecosystems to adapt of their own accord is currently poorly understood (WGII AR5 FOD Ch. 4), but some of the 'impacts' reported in this chapter, such as phenological changes, could be considered adaptive if they help the species to survive and flourish. Suggested general strategies for maximizing the adaptive capacity of ecosystems include: reducing non-climate impacts, monitoring climate impacts, maximizing landscape connectivity, and making protected area networks robust to future climate scenarios (Hannah, 2010; Shoo *et al*., 2011; Klorvuttimontara *et al*., 2011; Murthy *et al*., 2011; Mandych *et al*., 2012). In northeastern China, where climate change is expected to increase the risk of damaging forest fires, strengthening early warning and monitoring systems, paying attention to post-fire recovery, and the use of prescribed burning to reduce fuel loads are among the suggested strategies for adaptation (Tian *et al*., 2011). For Papua New Guinea, three general strategies have been suggested for adapting biodiversity conservation to climate change: conserving habitats across the full range of physical settings, including combinations of elevation and geology; protecting 'climatic refugia', where climate change is expected to be less than the regional mean; and increasing landscape connectivity (Game *et al*., 2011). A trial application of a formal process for adaptation to protect biodiversity in Vietnam used the 13 terrestrial ecoregions as basic planning units, for each of which social, economic and ecological trends were assessed, climate change scenarios identified, and key policy responses and actions developed (Booth *et al*., 2013). More generally, there is increasing recognition of the need to incorporate climate change adaptation into all forest conservation and development programs (e.g. in India; Chaturvedi *et al*., 2011; Murthy *et al*., 2011). There is a lack of scientifically well-founded recommendations and programs aimed at development of adaptation plans for the forest-tundra ecotone in North Asia at the state level (Anisimov *et al*., 2010). Comprehensive monitoring, assessments and projections that can anticipate numerous development scenarios are needed to elaborate a plan for adaptation to the cumulative effects of resource development, climate change, and demographic changes that are occurring (Walker *et al*., 2011). Similar problems are widespread in other parts of Asia, although awareness of the need for adaptation plans is increasing.

At the species level, distribution models are increasingly used to forecast the potential future distributions of species in the face of climate change, identifying areas where the species is most likely to persist and where it is most threatened, as well as potential new habitats (e.g., Higa *et al.*, 2013; Yu *et al.*, 2013). Restoration of ecological habitats within and between protected areas may help facilitate the movement of species across climatic gradients in response to climate change (Klorvuttimontara *et al.*, 2011; Hughes *et al.*, 2012). Key seed dispersal agents may need to be protected because of their potential role in long-distance plant movements in fragmented landscapes (Corlett, 2009). Assisted migration (or 'managed translocation') of genotypes and species is an increasingly common suggestion for plants and animals where adjustments to climate change are constrained by natural rates of movement, although the risks and benefits in each case need to be considered carefully (e.g. Liu *et al.*, 2010; Olden *et al.*, 2010; Tchebakova *et al.*, 2011; Ogawa-Onishi *et al.*, 2011; Dudgeon, 2012; Ishizuka and Goto, 2012). *Ex situ* conservation can provide back-up for some of the populations and species that are most at risk from climate change (Chen *et al.*, 2009).

24.4.3. Coastal Systems and Low-Lying Areas

24.4.3.1. Sub-Regional Diversity

Asia's long coastline includes the full global range of muddy, sandy, and rocky shore types, as well as extensive estuarine systems. Asia's tropical and subtropical coasts support an estimated 45% of the world's total mangrove forest and include the most mangrove-rich country (Indonesia) and the largest single tract of mangrove forest (the Sundarbans of Bangladesh and India) (Giri *et al.*, 2011). Low-lying areas near the coast of equatorial SE Asia support most of world's peat swamp forests (see also 24.8.2), which are a massive store of carbon, as well as extensive areas of other forested swamp types. Intertidal salt marshes are widespread along temperate and arctic coasts, while a variety of non-forested wetlands occur inland, including freshwater marshes and peat bogs. Asia also supports around 40% of the world's coral reef area (Spalding *et al.*, 2001; Burke *et al.*, 2011), mostly in SE Asia, with the most extensive reefs and the world's most diverse reef communities in the 'coral triangle' (in Indonesia, Malaysia, the Philippines, and Papua New Guinea; see also Chapter 30, this volume, Box 30-3). Seagrass beds are also widespread, although less well studied, and Asia supports the majority of the world's seagrass species (Green and Short, 2003). Six of the seven living species of sea turtle are found in the region and five species nest on Asian beaches (Spotila, 2004). Kelp forests and other seaweed beds are important on temperate coasts (Bolton, 2010; Nagai *et al.*, 2011). Permafrost and sea-ice influence coastal processes in the far north (Are *et al.*, 2008). The sea-ice itself supports a specialized community of mammals, including the polar bear, walrus, several species of seals, and the beluga and bowhead whales, as well as birds, fish and other species (Kovacs *et al.*, 2011; Chapter 28, Sections 28.2.3.3. and 28.2.3.4.).

24.4.3.2. Observed Impacts

Most of Asia's non-Arctic coastal ecosystems are under such severe pressure from non-climate human impacts that climate impacts are hard to detect. For example, observations of impacts from rising sea levels in Asia have reflected coastal subsidence rather than the impact of climate change, since most major deltas in Asia are now sinking (as a result of groundwater withdrawal, floodplain engineering, and trapping of sediments by upstream dams) at rates many times faster than the global sea-level is rising (Syvitski *et al.*, 2009). Widespread impacts can be attributed with *high confidence* to climate change, however, for coral reefs, where the temporal and spatial patterns of large-scale bleaching events generally correlate well with higher than normal sea surface temperatures (Hoegh-Guldberg, 2011; Krishnan *et al.*, 2011; Coles and Riegl, 2013; Lough, 2012). Increases in coastal water temperatures are also one of the most plausible explanations for widespread declines in beds of large seaweeds in temperate Japan: the Isoyake phenomenon (Nagai *et al.*, 2011). Warming coastal waters have also been implicated in the northwards expansion in Japanese waters of tropical and subtropical macroalgae and toxic phytoplankton (Nagai *et al.*, 2011), fish (Tian *et al.*, 2012), and tropical corals, including key reef-forming species (Yamano *et al.*, 2011), over recent decades. The decline of large temperate seaweeds and expansion of tropical species in southwest Japan

has been linked to rising sea surface temperatures (Tanaka *et al.*, 2012b), and the changes in the seaweed community have, in turn, impacted fish communities (Terazono *et al.*, 2012).

The impact of warming is also evident on sparsely populated Arctic coastlines, where erosion appears to be accelerating. In Arctic Asia, changes in permafrost and in storm wave energy caused by sea-level rise and sea-ice retreat have resulted in increased coastal retreat, in spite of the fact that most of the year coasts are protected by continuous ice cover (Are *et al.*, 2008; Razumov, 2010; Handmer *et al.*, 2012). In the central part of the Laptev Sea, coastal retreat has accelerated by 1.5-2 times in recent decades (Anisimov *et al.*, 2010). Average erosion rates of Asian Arctic coastlines range from 0.27 m/year (Chukchi Sea) to 0.87 m/year (East Siberian Sea). A number of segments in the Laptev Sea and in the East Siberian Sea are characterized by rates greater than 3 m/year (Lantuit *et al.*, 2012). The decline in the extent of arctic sea-ice documented in AR4 has continued, but the impacts on ice-dependent species and ecosystems in Arctic Asia are so far unclear [WG1 AR5 SOD Ch. 4; WG2 AR5 FOD Ch. 28].

24.4.3.3. Projected Impacts

It is *likely* that there will be an overall increase in marine biodiversity at temperate latitudes as temperature constraints on the distributions of warm-water taxa are relaxed, but biodiversity in tropical regions may fall if, as some evidence suggests, tropical marine species are already near their thermal maxima (Cheung *et al.*, 2009, 2010). An experimental study in Singapore found that the activity and survival of marine invertebrates in seven phyla was reduced by water temperatures only 2-3ºC above present (Nguyen *et al.*, 2011). In contrast, two shallow-water marine fish species from Indonesia showed exceptional tolerance of high temperatures (Eme *et al.*, 2011). Individual fish species are projected to shift their ranges northwards in response to rising sea surface temperatures (Tseng *et al.*, 2011; Okunishi *et al.*, 2012; Tian *et al.*, 2012). A combination of projected shifts in species distributions and expected changes in total primary production may lead to a regional redistribution of fisheries potential, with large declines in the tropics and large increases in high-latitude regions (Cheung *et al.*, 2010; WG2 AR5 FOD Ch. 6). A more recent study using a very different modeling approach produced broadly similar projections (Blanchard *et al.*, 2012). Another modeling study suggested that the combined effects of changes in distribution, abundance and physiology will reduce the body size of marine fishes, particularly in the tropics and intermediate latitudes (Cheung *et al.,* 2012). Projected impacts are greatest for coral reefs, where a continuation of current trends in sea-surface temperatures and ocean acidification suggests that existing coral-dominated reefs will largely disappear by mid-century (Vivekanandan *et al.*, 2009; Hoegh-Guldberg, 2011; Burke *et al.*, 2011). In the seas around Japan, warming would permit the expansion of coral habitats to the north, but ocean acidification is expected to limit this, with coral habitats sandwiched between excessive warming to the south and acidification in the north (Yara *et al.*, 2012). However, the capacity of coral communities to adjust by changes in species composition, or by the acclimation and/or adaptation of coral species, is not well understood (Ateweberhan and McClanahan, 2010; Fabricius *et al.*, 2011; Guest *et al.*, 2012; Howells *et al.*, 2012). The impacts of ocean acidification on other organisms are also currently poorly understood (Hendriks *et al.*, 2010; WGII AR5 FOD Ch. 6).

The uncertainties in future sea-level rises are still large (WG1 AR5 SOD Ch. 13). The major projected impacts include coastal flooding, increased erosion, and saltwater intrusion into surface and groundwater. In the absence of other impacts, coral reefs may grow fast enough to keep up with rising sea-levels (Brown *et al.*, 2011), but mangroves, salt marshes, and seagrass beds will decline unless they can move landwards or they receive sufficient sediment to keep pace, and beaches may erode (Gilman *et al.*, 2008; Bezuijen, 2011; Forbes, 2011). Loucks *et al.* (2010) predict a 96% decline in tiger habitat in Bangladesh's Sunderbans mangroves with a 28 cm sea-level rise if sedimentation does not increase surface elevations. Coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea-levels. However, in most river deltas, the global sea-level rise will continue to be outpaced by local subsidence for non-climatic reasons (Syvitski *et al.*, 2009).

Cyclones affect most of the Asian coastline, except in the far north, west, and 10º either side of the equator. Natural coastlines are resilient, but large cyclones can have a devastating impact on isolated ecosystem fragments. However, current trends in cyclone frequency and intensity are unclear (Seneviratne *et al.*, 2012; WG1 AR5 SOD Ch. 14; see Box CC-TC). A combination of cyclone intensification and sea-level rise could potentially result in a large increase in coastal flooding (Knutson *et al.*, 2010). Cyclones can also have a large impact on the productivity of coastal

waters through increased nutrient run-off and water circulation (Qiu *et al*., 2010). In addition to any changes in cyclone activity, sea turtles nesting beaches may be impacted by rising temperatures and sea-levels, but the capacity of turtle populations to adapt is not well understood (WGII AR5 FOD Ch. 6).

In the Asian Arctic it is *likely* that rates of coastal erosion will increase as a result of interactions between rising sea-levels and projected changes in permafrost and the length of the ice-free season (Pavlidis *et al*., 2007; Lantuit *et al*., 2012). The most sensitive region to potential increases in permafrost and sea surface temperatures on the Asian Arctic coast is the Kara Sea region (Lantuit *et al*., 2012). Sea level rise may have different influences on coastal processes depending on the sediment budget equilibrium, playing a minor role if there is a strong imbalance in the sediment budget, but appearing to be the main factor if the sediment budget is balanced (Leont'yev, 2008). The most prominent changes in the dynamics and morphology of the coastal zone are expected where the coasts are composed of loose permafrost rocks and are therefore subject to intensive thermal abrasion. Assuming that sea level will rise by 0.5 m over the next century, modeling studies predict that the rate of recession due to thermal erosion will increase 1.5- to 2.6-fold for the coasts of Laptev Sea, East Siberian sea and of West Yamal in the Kara Sea compared to the rate observed in first years of the XXI century. This rate will vary across the Asian Arctic coast from 3 to 9 m/year (Pavlidis *et al*., 2007).

24.4.3.4. Vulnerabilities to Key Drivers

As discussed in the previous section, offshore marine systems appear to be most vulnerable to rising water temperatures, plus the impacts of ocean acidification, particularly for calcifying organisms such as corals. Sea-level rise will be the key issue for many coastal areas, particularly if it is combined with changes in cyclone frequency or intensity, or in Arctic Asia, with a lengthening open-water season. The expected continuing decline in the extent of sea-ice in the arctic may threaten the survival of some ice-associated mammals and other organisms (WG1 AR5 SOD Ch. 4; WGII AR5 FOD Ch. 6), with the expansion of human activities in previously inaccessible areas an additional problem (Kovacs *et al*., 2011).

24.4.3.5. Adaptation Options

The connectivity of marine habitats and the relatively high dispersal abilities of many marine organisms should maximize the capacity for autonomous (spontaneous) adaptation in natural and semi-natural coastal systems and is expected to keep the extinction rate below that projected for terrestrial habitats (Cheung *et al*., 2009). Where natural connectivity is insufficient, as between the heat-tolerant coral populations of the Arabian/Persian Gulf and the Southeast Asian reefs threatened by rising temperatures, than 'assisted colonization' (by moving adult fragments or larval stages) is a possible option, although only as a last resort (Coles and Riegl, 2013). Creating marine protected areas in locations where sea surface temperatures are projected to change least may increase their future resilience (Levy and Ban, 2013). 'Hard' coastal defenses, such as dykes, levees and sea walls, may protect settlements, but at the cost of preventing adjustments by mangroves, salt marshes and seagrass beds to rising sea-levels. The acquisition of landward buffer zones that provide an opportunity for future inland migration could mitigate this problem (Erwin, 2009), but is rarely practical. Large sections of Asia's coastline are already highly degraded and there are many opportunities for restoration of coastal systems (Crooks *et al*., 2011).

24.4.4. Food Production Systems and Food Security

It is projected that climate change will affect food security in the middle of the 21st century, with the largest numbers of food-insecure people located in South Asia (Porter *et al*., 2014 Chapter 7).

24.4.4.1. Sub-Regional Diversity

AR4 Section 10.4.1.1 pointed out that there will be regional differences in the impacts of climate change on food production. Research since then has validated this divergence and new data are available especially for West and Central Asia (see Tables 24-5 and 24-6). These differences will be apparent in the discussion below. In addition, new studies have supplied more detailed data about the impacts on crop production. In AR4 Section 10.4.1, climate change was projected to lead mainly to reductions in yield. New research shows there will also be gains for specific regions and crops in given areas. Thus, the current assessment encompasses an enormous variability depending on the regions and the crops grown.

24.4.4.2. Observed Impacts

While there is consensus that climate change will affect food production systems and food security, the precise nature and timing of these impacts, as well as their implications for human livelihoods, are still uncertain (Hertel *et al*., 2010). There are limited data in Asia for observed impacts of climate change on food production systems. In Jordan, it was reported that in 1999, the total production and average yield for wheat and barley were the lowest among the years 1996 to 2006. This could be explained by the low rainfall during that year, which was 30% of the average (high confidence in detection, low confidence in attribution). These results suggest that both crops are vulnerable to climatic variations (Al-Bakri *et al*., 2010). In China, rice yield responses to recent climate change at experimental stations were assessed for the period 1981–2005 (Zhang *et al*. 2010). The study concluded that there are variable climate to yield relationships, considering inter-annual variations at a regional scale. In some places, yield fluctuations were positively correlated with temperature when they were also positively related with solar radiation. However, in other places, lower yield with higher temperature was accompanied by a positive correlation between yield and rainfall (high confidence in detection, high confidence in attribution). Crop responses to high temperatures can be accurately estimated from experiments in controlled environments; however, such experiments are generally not feasible given the large number of crops. Instead, the general effects of climate change on a wide variety of crops can be estimated by collecting and analyzing data from various agricultural systems on yield changes due to recent regional temperature increases. In Japan, where mean air temperature has risen at 1ºC per the past 100 years, information on changes in agricultural production (cereal, soybean, fruit tree, vegetable and livestock), were collected by surveys of the public institutes of agricultural research in 47 prefectures. Recent effects of warming were analyzed by comparing those data to literature on relations between crop growth and temperature (Sugiura, et al, 2012). Effects of recent warming, include phenological changes in many crops, increases in fruit coloring disorders and incidences of chalky rice kernels, reductions in yields of wheat, barley, vegetables, flowers, milk and eggs, and alterations in the type of disease and pest.

Another possible approach to assessing observed impacts of climate change is to combine local knowledge with scientific assessments. For example, the nomadic herders of Mongolia demonstrated a detailed understanding of weather and climate, including an account of climatic change that integrates multiple indicators (Marin, 2010). However, their evidence of change is only partly supported (or even contradicted) by meteorological records, larger scale predictions and general circulation models.

24.4.4.3. Projected Impacts

Production. AR4 Section 10.4.1.1 mainly dealt with cereal crops (rice, wheat corn). Since then, impacts of climate change have been modeled for additional cereal crops and sub-regions. In semi-arid and arid regions of Western Asia, a review paper (Ratnakumar *et al*., 2011) has shown that rainfed agriculture is sensitive to climate change both positively and negatively. A rise in CO_2 concentration may benefit the semi-arid crops by increasing crop water-use efficiency and net photosynthesis leading to greater biomass, yield and harvest index. C_3 plants responded with a higher average increment in biomass production than C_4 plants. For example, wheat yield increased by 10-20% with elevated CO_2 (350 ppm to 700 ppm). In Yarmouk basin, Jordan, simulation with DSSAT showed that wheat and barley yields will decline by 10-20% and 4-8% respectively with a 10-20% reduction in rainfall (Al-Bakri *et al*., 2010). Conversely, with an increase in rainfall of 10–20% the expected yield increased by 3–5% for barley and 9–

18% for wheat. However increased air temperatures had mixed results. Increasing temperature by 1, 2, 3 and 4°C resulted in deviations from expected yield of -14%, -28%, -38% and -46% for barley and -17%, +4%, +43% and +113% for wheat.

In the Swat and Chitral districts of Pakistan (mountainous areas with average altitudes of 960 and 1500 m above sea level, respectively), there were mixed results as well (Hussain and Mudasser, 2007). Projected temperature increases of 1.5 and 3 °C would lead to wheat yield declines (by 7% and 24% respectively) in Swat district but increases (by 14% and 23%) in Chitral district. If precipitation increases by 5–15% during the growing season, the study showed a negligible impact on wheat yield. Also in Pakistan, modeling studies show that wheat yields are expected to decline by 6-8 % under B2 and A2 scenarios by the 2080s, whereas rice yields decline by 16-19% under the same conditions (Iqbal et.al. 2009). In India, climate change impacts on sorghum were analyzed using the Info Crop-SORGHUM simulation model (Srivastava *et al*., 2010). A changing climate was projected to reduce monsoon sorghum grain yield by 2-14% by 2020, with worsening yields by 2050 and 2080. In addition, climate change was projected to reduce winter crop yields up to 7% by 2020, up to 11% by 2050 and up to 32% by 2080. In the Indo-Gangetic Plains, a higher reduction in wheat yields is projected (see below), unless appropriate cultivars and crop management practices are adopted (Ortiz *et al*., 2008).

In China, modeling studies of the impacts of climate change on crop productivity have had mixed results. Rice is the most important staple food in Asia. Studies show that climate change will alter productivity in China but not always negatively. With rising temperatures, the process of rice development accelerates and reduces the duration for growth. In one study, using the SRES B2 scenario without a CO_2 fertilization effect, the average simulated yield of irrigated rice along the Yangtze River decreased by 14.8%, and the yield of rain-fed rice decreased by 15.2% by 2021–2050 (Shen *et al*., 2011). With CO_2 fertilization factored in, the simulated yield of irrigated rice decreased by 3.3% and the yield of rain-fed rice decreased by 4.1% on average. Tao *et al*. (2008) reported similar findings using all 20 combinations of four scenarios (A1F1, A2, B2, B1) and five GCMs (HadCM3, PCM, CGCM2, CSIRO2, ECHAM4). Without CO_2 fertilization effects, the growing period would be shorter and yield would decrease. The median values of yield decrease ranged from 6.1% to 18.6%, 13.5% to 31.9%, and 23.6% to 40.2% for air temperature increases of 1, 2, and 3 °C, respectively. However, if CO_2 fertilization effects were included, the median values of yield changes ranged from -10.1% to 3.3%, -16.1% to 2.5%, and -19.3% to 0.18% for the same temperature increases. Other studies have also shown that higher temperature would seriously lower rice yields due to shorter crop duration (Xiong *et al*., 2010; Yao *et al*., 2007).

In contrast, Zhang *et al*. (2010) reported that rice yield responses to temperature were broadly positive, which means that yields were not limited by an increase in minimum, maximum or mean temperatures. The authors hypothesize that solar radiation level is the major climatic driver for yield fluctuations at these Chinese experimental stations, and the positive yield correlation to temperature can be explained by the correlations between radiation and temperature, which were positive at most studied stations. Thus, the positive effect of radiation on rice yield overwhelmed temperature's negative effect.

Wassman *et al*. (2009a, 2009b) provide the most comprehensive review of climate change impacts and adaptation for rice in the region. A key conclusion of the report is that, in terms of risks of increasing heat stress, there are parts of Asia where current temperatures are already approaching critical levels during the susceptible stages of the rice plant. These include: Pakistan/North India (October), South India (April, August), East India/Bangladesh (March-June), Myanmar/Thailand/Laos/Cambodia (March-June), Vietnam (April/August), Philippines (April/June), Indonesia (August) and China (July/August).

There have also been simulation studies for other crops in China. In the Huang-Huai-Hai Plain, China's most productive wheat growing region, modeling indicated that winter wheat yields would increase on average by 0.2 Mg ha-1 in 2015-2045 and by 0.8 Mg ha-1 in 2070-2099, due to warmer nighttime temperatures and higher precipitation, under A2 and B2 scenarios using the HadCM3 model (Thomson *et al*., 2006). Yields were positively influenced by increasing precipitation projected under the climate change scenarios, with the highest average yields in the 2085 time period when the precipitation increase was greatest. Liu *et al*. (2010c) worked on a wheat-maize cropping system in the same plain. Generally, climate change (2 and 5ºC increase in temperature; precipitation increasing and decreasing by 15 and 30%; atmospheric CO_2 enrichment to 500 and 700 ppmv) would result in a mean relative yield

change (RYC in %) of −10.33% with a standard deviation of 20.27%, and the lowest and highest RYC values of −46% and +49%. However when CO_2 fertilization effects were included, a positive change in RYC was obtained. In addition, increasing precipitation mitigates the negative impact of increasing temperatures on yield. On average, without CO_2 enrichment, the mean RYC for irrigated land is less negative (−18.5±12.6%) than for rainfed land (−21.5±14.2%), but with CO_2 enrichment there was no significant difference between irrigated and rainfed yields. These results show that CO_2 enrichment reduces the impact of irrigation.

The potential climate change impacts on the productivity of five major crops (canola, corn, potato, rice, and winter wheat) in eastern China have also been investigated using the RegCM3 regional climate model under the A2 scenario (Chavas *et al*., 2009). Aggregate potential productivity (i.e. if the crop is grown everywhere) with CO_2 fertilization increased 6.5% for rice, 8.3% for canola, 18.6% for corn, 22.9% for potato, and 24.9% for winter wheat, although with significant spatial variability for each crop. However, without the enhanced CO_2-fertilization effect, potential productivity declined in all cases, by 2.5-12%.

Extreme weather events are expected to negatively affect agricultural crop production (IPCC, 2012; Handner *et al*., 2012). For example, extreme temperatures could lower yields of rice (Tian *et al*., 2010; Mohammed and Tarpley, 2009). With higher precipitation, flooding could also lead to lower crop production [SREX Ch. 4]. For example, cyclone Sidr which hit Bangladesh in 2007 caused more than 3,000 deaths and the damage to agriculture was estimated to be in excess of US$3 billion (Paul, 2009; Islam *et al*., 2011; Hasegawa, 2008). Another example is from the Philippines which lies in the typhoon belt with an average of 20 tropical cyclones per year in addition to other extreme weather events (Yumul *et al*., 2011; Yumul *et al*., 2010). One study showed that relative losses per crop as part of the annual farm household income due to one tropical cyclone for yellow corn, banana, and rice were 64%, 24%, and 27%, respectively (Huigen and Jens, 2006).

Farming systems and crop areas. Since AR4 [WG2 AR4 10.4.1.2], more information is available on the impacts of climate change on farming systems and cropping areas in more countries in Asia and especially in Central Asia. In general, recent studies validate the northward shifts of crop production with current croplands under threat from the impacts of climate change as mentioned in AR4.

Climate change threatens the food security of West Asia where most of drylands are comprised of rangelands (Thomas, 2008). The region has the world's lowest rate of renewable water resources per capita and is already the major grain importing region of the world. Climate change will exacerbate existing threats to food production and security such as high population growth rates, water scarcity, and land degradation.

In Central Asia, changes in temperature and precipitation regimes could to lead to changes in the area suitable for rain-fed production of cereals and other food crops, changing sustainable stocking rates, and modifications of crop irrigation requirements (Lioubimtseva and Henebry, 2009). The region is expected to become warmer during the coming decades and increasingly arid, especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan. The impacts on food production will vary by country. Some parts of the region could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters and slight increase in winter precipitation), while others could be losers (particularly western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase already extremely high water demands for irrigation, and exacerbate the already existing water crisis and human-induced desertification). In addition Central Asia and the Caucasus is the second most vulnerable region of the world to crop loss by pollinator loss (Christmann and Aw-Hassanb, 2011). Honey bees (*Apis mellifera*) are important in crop pollination, but bees are highly sensitive to change of temperatures and can provide service only on sunny, warm, dry and not too windy days. The tolerance of local honey bees to climate change needs further elucidation.

In India, the Indo-Gangetic Plains are under threat of a significant reduction in wheat yields (Ortiz *et al*., 2008). This area produces 90 million tons of wheat grain annually (about 14-15% of global production). Climate projections based on a doubling of CO_2 using a CCM3 model downscaled to a 30 arc-second resolution as part of the Worldclim data set showed that there will be a 51% decrease in the most favorable and high yielding area due to heat stress. About 200 million people (using the current population) whose food intake relies on crop harvests would experience adverse impacts.

In Sri Lanka, a number of studies reviewed by Eriyagama *et al*. (2010) showed varying results. Tea cultivation at low and mid-elevations is more vulnerable to the adverse impacts of climate change than at high elevations. Projected coconut production after 2040 in all climate scenarios will not be sufficient to meet local consumption. The total impact on agriculture (rice, tea, rubber and coconut) production ranges from a decrease of US$96.4 million (-20%) to an increase of US$342 million (+72%) depending on the climate scenarios.

In eastern China, a study showed corn and winter wheat production would benefit significantly from climate change in the North China Plain (Chavas *et al*., 2009). Rice would remain dominant in the southeast but emerges in the northeast, potato and corn yields would become viable in the northwest, and potato yields suffer in the southwest. The study defined vulnerable and emergent regions under future climate conditions as those having a greater than 10% decrease or increase in productivity, respectively.

Rice growing areas are also expected to shift with climate change throughout the region. In Japan, increasing water temperature (1.6–2.0 °C) could lead to a northward shift of the isochrones of safe transplanting dates for rice seedlings (Ohta and Kimura, 2007). As a result, rice cultivation period will be prolonged by approximately 25–30 days. This will allow greater flexibility in the cropping season than at present, resulting in a reduction in the frequency of cool-summer damage in the northern districts. Iizumi *et al*., (2007) assesses the potential reduction of cool-summer damage in northern Japan and supports this conclusion. In addition, ensemble-based probabilistic assessments for rice-yield in Japan are available from Iizumi *et al*., (2011) and Okada *et al*., (2011).The latter paper assesses the impacts on both rice yield and eating quality.

In Indonesia, a marked increase in the probability of a 30-day delay in monsoon onset in 2050 is projected, as a result of changes in the mean climate, from 9-18% today (depending on the region) to 30-40% at the upper tail of the distribution (Naylor *et al*. 2007). In addition, there would be an increase in precipitation later in the crop year (April-June) of around 10% but a substantial decrease (up to 75% at the tail) in precipitation later in the dry season (July-September). However, the increase in April-June rainfall would not compensate for reduced rainfall later in the crop year, particularly if water storage for agriculture was inadequate. Secondly, the extraordinarily dry conditions in July-September could preclude the planting of rice and all other crops without irrigation during these months by 2050. In Sri Lanka, studies on future rice production have had mixed results. A study reviewed by Eriyagama *et al*., 2010 showed that a 0.1-0.5°C increase in temperature could depress rice yield by approximately 1-5%. However, another study suggested that rice yields will respond positively (increases of 24 and 39% in the two seasons) to elevated CO_2 even at higher growing temperatures (>30°C) in subhumid tropical environments. The real threat to rice cultivation might be changes in the amount of precipitation and its temporal distribution. Climate change is expected to affect water supply for rice cultivation in Sri Lanka (De Silva *et al*., 2007). During the wet season, impacts on irrigated rice production are projected to be positive in the extreme south of the country, confirming results of a previous study. However, the impacts will be negative across most of Sri Lanka. During the wet season, average rainfall would decline by 17% (A2) and 9% (B2), with rains ending earlier. Consequently, the average paddy irrigation water requirement would increase by 23% (A2) and 13% (B2).

Similarly in the whole of China, Xiong *et al*. (2010) reported there would be insufficient water for agriculture in the 2020s and 2040s, due to increases in water demand for non-agricultural uses, using the HadAM3H GCM and the PRECIS regional model, especially under the A2 scenario (see also 24.4.1.3). The proportion of water demanded by rice (which consumes 79% of the total baseline potential water demand of three grain crops) is projected to increase, because of significant increases in the projected water demand by rice under A2 (+62% for the 2020s above the baseline, and +58% for the 2040s), and moderate increases under B2 (5% and 2% for the 2020s, and the 2040s, respectively). However, due to increases in demand in other sectors (domestic, environmental and industrial) captured in the socio-economic scenarios (SES), the water available for agriculture decreases dramatically under A2 by 5% (2020s) and 21% (2040s) and under B2 by 3% (2020s) and 16% (2040s).

High quality fruits are cultivated in a narrow temperature zone. In Japan, the current main apple producing districts have annual mean temperature of 6-14°C with mean temperature of 13-21°C from April to October. Many parts of these districts may become unfavorable for apple cultivation by the 2060s (Sugiura *et al*., 2005).

Fisheries and aquaculture. Asia dominates the global production of food from both capture fisheries and aquaculture, with China, Indonesia, India, the Philippines and Myanmar in the top ten for capture fisheries and China, India, Vietnam, Indonesia, Thailand, Bangladesh, the Philippines and Japan in the top ten for aquaculture (FAO 2010). More than half of the global marine fish catch in 2008 was in the West Pacific and Indian Ocean, and the lower Mekong River basin supports the largest freshwater capture fishery in the world. Fish production is also a vital component of regional livelihoods, with 85.5% of the world's fishers (28 m) and fish farmers (10 m) in Asia in 2008. Many more people engage in capture fisheries part-time. Fish catches in the Asian Arctic are relatively small, but are important for local cultures and regional food security (Zeller *et al*. 2011).

Inland fisheries will continue to be vulnerable to a wide range of on-going threats, including overfishing, habitat loss, water abstraction, drainage of wetlands, pollution, and dam construction, making the impacts of climate change hard to detect. Most concerns have centered on rising water temperatures and the potential impacts of climate change on flow regimes, which in turn are expected affect the reproduction of many fish species (Allison *et al*., 2009; Barange and Perry, 2009; Bezuijen, 2011; Dudgeon, 2011; see also section 24.4.2.3). Sea-level rise is expected to impact both capture fisheries and aquaculture production in river deltas (De Silva and Soto, 2009). For marine capture fisheries, Cheung et al. (2009, 2010) used a dynamic bioclimate envelope model to project the distributions of 1066 species of exploited marine fish and invertebrates for 2055, based on the SRES A1B scenario. This analysis suggests that climate change may lead to a massive redistribution of fisheries catch potential, with large increases in high-latitude regions, including Asian Russia, and large declines in the tropics, particularly Indonesia. Other studies have made generally similar predictions, with climate change impacts on marine productivity expected to be large and negative in the tropics, in part because of the vulnerability of coral reefs to both warming and ocean acidification (see also section 24.4.3.3), and large and positive in arctic and subarctic regions, because of sea-ice retreat and poleward species shifts (Doney *et al*., 2012; Sumaila *et al*., 2011; Blanchard *et al*., 2012). Predictions of a reduction in the average maximum body weight of marine fishes by 14-24% are an additional threat to fisheries (Cheung et al., 2012). Studies on the economically important yellowtail in Japanese waters have shown a northward extension in the winter distribution during the warm 1990s and project a 3º northward shift in latitude by 2050 under the A1B scenario (Tian *et al*., 2012). Similarly, the important Pacific saury is expected to shift its range polewards by < 6º (Tseng *et al*., 2011)

Future food supply and demand. AR4 Section 10.4.1.4 was largely based on global models that included Asia. There are now several quantitative studies of both the whole continent and individual countries. In general, these show that the risk of hunger, food insecurity and loss of livelihood due to climate change will be high, as discussed below.

Rice is a key staple crop in Asia and 90% or more of the world's production is from Asia. An Asia-wide study revealed that climate change scenarios (using 18 GCMs for A1B; 14 GCMs for A2 and 17 GCMs for B1) would reduce rice yield over a large portion of the continent (Masutomi *et al*., 2009). The most vulnerable regions were western Japan, eastern China, the southern part of the Indochina peninsula, and the northern part of South Asia. In these areas, a rise in temperature during the growing periods would be the main cause of the decreases in yield. The negative impacts of climate change were diminished, but not totally eliminated, by the positive effect of CO_2 fertilization. In a global study, Hertel *et al*. (2010) showed that under the low-productivity scenario (due to climate change), prices for major staples would rise 10–60% by 2030 in Asia. Poverty rates in some non-agricultural household could rise by 20–50% in parts of Asia and fall by significant proportions for agriculture households.

In Russia, climate change may also lead to "food production shortfall", which was defined as an event in which the annual potential (i.e. climate-related) production of the most important crops in an administrative region in a specific year falls below 50% of its climate-normal (1961–1990) average (Alcamo *et al*., 2007). The frequency of shortfalls in the main crop growing regions is around 2 years/decade under climate baseline conditions, but could climb to 5–6 years/decade in the 2070s (using the ECHAM and HadCM3 models and the A2 and B2 scenarios). The increasing shortfalls were attributed to severe droughts. The study estimated that the number of people living in these regions may grow to 82–139 million in the 2070s. Increasing frequency of extreme climate events will pose an increasing threat to the security of Russia's food system.

Tchebakova *et al*., (2010) analyzed the agroclimatical potential of Central Siberia in the 21st century. They concluded that climate changes to come for the years 2020 and 2080 (HadCM3 with B1 and A2 scenarios) will in general be beneficial for this territory. "From 50 to 85% of Central Siberia is predicted to be climatically suitable for agriculture by the end of the century, and only soil potential would limit crop advance and expansion to the North. Crop production could increase twofold. Future Siberian climatic resources could provide the potential for a great variety of crops to grow that previously did not exist in these lands." (Tchebakova *et al*., 2010).

Most of the studies reviewed in the previous sections predict negative impacts of climate change on crop yield and therefore presumably on food supply. Climate change may also lead to an increase in food supply in some countries. For example, climate change may provide a windfall for wheat farmers in parts of Pakistan. Warming temperatures would make it possible to grow at least two crops (wheat and maize) a year in the mountain areas (Hussain and Mudasser, 2007). It will also allow more time for land preparation for the subsequent maize crop, with beneficial effects on yield. The increased productivity of the wheat–maize cropping system is expected to improve food security, increase farm income and reduce overall poverty of the farm households in the area.

Pests and diseases. AR4 contained a generalization about the possibility of increasing pests and diseases due to climate change. Since then there have been very few studies of climate change impacts on pests and diseases which support this conclusion. For example in South Asia, warming temperatures could lead to higher incidence of spot blotch (caused by *Cochliobolus sativus*), already a serious constraint on wheat production at present. An increasing mean minimum temperature in March showed a positive relationship with spot blotch severity (Sharma *et al*., 2007). Sharma *et al*. (2010) recommended the regular monitoring of pest populations in future to determine if a threshold has been exceeded and if control measures are required. This information will also be valuable for forecasting pest populations, severity of damage, and pest outbreaks. Climate change may also modify the effectiveness of biological control (e.g. natural enemies), biopesticides, and synthetic insecticides.

24.4.4.5. Adaptation Options

Since AR4, there have been additional studies of recommended and potential adaptation strategies and practices in Asia (see Table 24-7) and there is new information for West and Central Asia. There are also many more crop-specific and country-specific adaptation options available.

[INSERT TABLE 24-7 HERE
Table 24-7: Summary of adaptation options for agriculture in Asia.]

Farmers have been adapting to climate risks for generations. Indigenous and local adaptation strategies have been documented for Southeast Asia (Peras *et al*., 2008; Lasco *et al*., 2011; Lasco *et al*., 2010) and could be used as a basis for future climate change adaptation. Social and institutional aspects of climate change adaptation have also been investigated in the Philippines. Agent-based modeling showed that smallholder farmers face a number of constraints in adapting new technologies to cope with climate risks (Acosta-Michlik and Espaldon, 2008). In general, lack of knowledge and money were the most important reasons for not adopting drought-related technical measures. In the above studies there are many non-farm related adaptation strategies, such as selling valuables, sending family workers to work overseas, and migrating to another location. Local government units can also play a catalytic role in climate change adaptation as shown by the experience of Albay province in the Philippines, which has been in the forefront of climate change adaptation activities in the country (Lasco *et al*., 2013; Lasco *et al*. 2008). The main initiatives include legislating local policies on climate change adaptation, integrating climate change adaptation and disaster risk management, and the implementation of on-the ground activities. In addition, they have become a national player in climate change adaptation in the Philippines.

24.4.5. Human Settlements, Industry, and Infrastructure

24.4.5.1. Sub-Regional Diversity

Asia, being the largest continent in the world in terms of area and population, is both diverse and complex. Sustainable development will be challenged as climate change compounds the pressures that rapid urbanization, industrialization and economic development have placed on natural, social and economic resources (IPCC, 2007b). Settlement patterns, urbanization and changes in socioeconomic conditions greatly influence trends in exposure and vulnerability to climate extremes (IPCC, 2012). Population distribution is uneven within Asia, with two subregions, East Asia and South-Central Asia, accounting for 80% of the total (UNFPA, 2010). Moreover, a few Asian countries account for 69% of the world's rural population, with India and China alone accounting for 45%, followed by Bangladesh, Indonesia and Pakistan, each with over 100 million rural inhabitants. Much of the increase projected for the world population is expected to come from 39 high-fertility countries, of which nine are located in Asia. Although population growth rates have been decreasing in almost all subregions of Asia since 2000 (UN ESCAP, 2011), growth continues to be high, particularly in countries with low human development performance, leading to large populations with limited adaptive capacity (World Bank 2012).

Notwithstanding considerable challenges in measurement (Satterthwaite 2006), around one in every five urban dwellers in Asia lives in large urban agglomerations and almost 50% of urban dwellers live in small cities (UN, 2012). However, there is wide subregional variation. For example, North and Central Asia are the most urbanized areas, with over 63% of the population living in urban areas, with the exception of Kyrgyzstan and Tajikistan, followed by East and Northeast Asia, where rapid urbanization in the last two decades has led to half the population living in cities (UN ESCAP, 2011; UN Habitat, 2010). South and Southwest Asia are the least urbanized subregions, with only a third of their populations living in urban areas. However, these regions have the highest urban population growth rates within Asia at an average of 2.4% per year during 2005-2010 (UN-ESCAP, 2011). By the middle of this century, Asia's urban population will increase by 1.4 billion and will account for over 50% of the global population, with China and India projected to account for about a third of the increase in the coming decades (UN, 2012).

Most Asian countries are witnessing significant development opportunities as well as a myriad of challenges. In 2010, seven Asian economies (China, India, Indonesia, Japan, Korea, Malaysia and Thailand) shared 78% of Asia's population and 87% of Asia's GDP (ADB, 2011). However, across all the subregions of Asia, poor people and urban slum dwellers tend to live in high-risk areas, such as unstable slopes and flood plains, and often cannot afford well-built houses. The poorest people are expected to suffer the most from climate change (UN-Habitat, 2011).

24.4.5.2. Observed Impacts

Asia has in the past suffered from many disasters related to natural hazards (IPCC, 2012). The data also reveals a strong increase in loss and damage caused by such disasters over recent years (Munich Re 2011; CRED 2012). However, the literature suggests that this increase can be attributed to climate change only with low confidence [18.4.1]. Asia experienced the highest number of weather- and climate-related disasters in the world during the period 2000-2008 and suffered huge economic losses, accounting for the second highest proportion (27.5%) of the total global economic loss. Losses of human lives, cultural heritage, and ecosystem services are difficult to value and monetize, and thus are poorly reflected in estimates of monetary losses. Impacts on the informal or undocumented economy, as well as indirect effects, can also be very important in some areas and sectors, but are generally not counted in reported estimates of losses (IPCC, 2012).

Flood mortality risk is heavily concentrated in Asia. The top ten countries, based on numbers of lives lost, are India, Bangladesh, China, Vietnam, Cambodia, Myanmar, Sudan, Korea, Afghanistan and Pakistan (UNISDR, 2009). Severe floods in Mumbai in 2005 following 944 mm rainfall within 24 hours have been attributed to both climatic factors and non-climatic factors, such as lack of early warning, preparedness and response capacities at the local level, lack of modern rain gauges, poor urban drainage systems, blockages in the natural drainage channels, poor waste management, poor urban planning, lack of civic sense among citizens, among others (IPCC, 2012; Surjan *et*

al., 2009). Yet, despite the increasing number of people living in floodplains, strengthening of capacities to address the mortality risk associated with major weather-related hazards, such as floods, has resulted in a downward trend in mortality risk relative to population size, as in East Asia, where mortality risk is now at a third of its 1980 level (UNISDR, 2011). Note also that many areas of Asia have seasonal shortfalls in the availability of water, which is also a growing crisis (ADB *et al*., 2012).

24.4.5.3. Projected Impacts

A large proportion of Asia's population lives in low elevation coastal zones that are particularly at risk from climate change hazards, including sea-level rise, storm surges and typhoons [5.3.2.1; 8.2.2.5; Box CC-TC]. Human settlements include rural villages, small and mid-sized cities, megacities and periurban fringes, but most attention in terms of projected climate change impacts has been given to Asia's urban areas, particularly to megacities. Depending on the region, half to two-thirds of Asia's cities with 1 million or more inhabitants are exposed to one or even multiple hazards, with floods and cyclones being the most important ones (UN, 2012). The risk of underestimating the impact of rare or more severe natural disasters on urban areas is high. Asian mega-deltas are particularly susceptible to extreme impacts due to a combination of high-hazard river, coastal flooding and increased population exposure from expanding urban areas with large proportions of high vulnerability groups (IPCC, 2012).

Floodplains. Three of the world's five most populated cities (Tokyo, Delhi and Shanghai) are located in areas with high risk of floods (UN, 2012). Flood risk and associated human and material losses are heavily concentrated in India, Bangladesh, and China. At the same time, the East Asia region in particular is experiencing increasing water shortages, affecting its socioeconomic, agricultural, and environmental conditions negatively, which is attributed to lack of rains and high evapotranspiration, as well as over-exploitation of water resources. Any increase in climatic and weather extremes is expected to aggravate the problem of pollution and flooding. Aging infrastructure may hinder the operation of sewer systems, particularly in Central Asia (IPCC, 2012).

Coastal Areas. By the year 2025, 70% of Asia's urban population will live in the coastal areas, with the majority located in low-elevation coastal zones (Balk *et al*., 2009). Climate change is expected to increase the risk of cyclones, flooding, landslides and drought, the adverse events which have a direct influence on urban and rural settlements, infrastructure and industries alike. Large parts of South, East and Southeast Asia are exposed to a high degree of cumulative climate-related risk (UN-Habitat, 2011). Asia has more than 90% of the global population exposed to tropical cyclones (IPCC, 2012; see Box CC-TC). Damage due to storm surge is sensitive to any change in the magnitude of tropical cyclones. For example, projections for the inner parts of three major bays (Tokyo, Ise, and Osaka) in Japan indicated that a typhoon that is 1.3 times as strong as the design standard, combined with a sea-level rise of 60 cm, would cause damage costs of about US$3, 40, and 27 billion, respectively, in the investigated bays (IPCC, 2012; Suzuki, 2009).

Exposure of the world's large port cities (population exceeding 1 million inhabitants in 2005) to coastal flooding due to sea-level rise and storm surge now and in the 2070s have been estimated, taking into account scenarios of socio-economic and climate changes. About 40 million people (0.6% of the global population or roughly 1 in 10 of the total port city population in the cities considered) are currently exposed to a 1 in 100 year coastal flood event (Hanson *et al*. 2011). The bulk of exposed assets in Asia are currently concentrated in Japan, where 46% of the population, 47% of industrial production and 77% of commercial sales are concentrated in ocean-front cities, towns and villages (Yasuhara, *et al*., 2011). Mumbai, Kolkata, Dhaka, Guangzhou, Ho Chi Minh City, Shanghai, Bangkok, Rangoon, and Hai Phòng will be the cities with the greatest population exposure to coastal flooding in 2070 (IPCC, 2012). Port authorities from around the world perceive sea-level rise as an issue of great concern (Becker *et al*., 2012). There is consensus that planned rapid expansion of ports should take into account adaptation measures as the new infrastructure may still be in use at the end of the century.

Population and Assets. Asia has a large – and rapidly expanding – proportion of the global urban exposure and vulnerability related to climate change hazards [SREX 4.4.3]. By the 2070s, the top Asian cities in terms of population exposure (including all environmental and socioeconomic factors) are expected to be Kolkata, Mumbai, Dhaka, Guangzhou, Ho Chi Minh City, Shanghai, Bangkok, Rangoon, and Hai Phòng (Nicholls *et al*., 2008). The

top Asian cities in terms of assets exposed included Guangdong, Kolkata, Shanghai, Mumbai, Tianjin, Tokyo, Hong Kong, and Bangkok. Hence, cities in Asia, particularly those in China, India and Thailand, become even more dominant in terms of population and asset exposure, as a result of the rapid urbanization and economic growth expected in these countries. This study also estimates that by 2070, population and asset exposure within Asia's large port cities will be disproportionately concentrated in China, India, Japan, Thailand, Vietnam, Bangladesh, Myanmar and Indonesia (Nicholls *et al*., 2008). Vulnerability and potential impacts in Asia's small and medium sized cities is less understood despite their demographic importance (see above). This is partially due to questions around measurement and administrative definitions (Satterthwaite, 2006).

In line with the rapid urban growth and sprawl in many parts of Asia, the periurban interface between urban and rural areas deserves particular attention when considering climate change vulnerability (see also chapter 18.4.1). Garschagen et al. (2011) find, for example, that periurban agriculturalists in the Vietnamese Mekong Delta are facing a multiple burden since they are often exposed to overlapping risks resulting from (a) socio-economic transformations, such as land title insecurity and price pressures; (b) local biophysical degradation, as periurban areas serve as sinks for urban wastes; and (c) climate change impacts, as they do not benefit from the inner-urban disaster risk management measures. Nevertheless, the periurban interface is still underemphasized in studies on impacts, vulnerability and adaptation in Asia. Settlements on unstable slopes or landslide-prone areas face increased prospects of rainfall-induced landslides (IPCC, 2012).

Water-scarcity, especially in summer, is now beyond the control of local governments in urban areas in a number of cities and towns in Asia. Groundwater sources, which are affordable means of high-quality water supply in cities of developing countries, are threatened due to over-withdrawals. Aquifer levels have fallen by 20-50 meters in cities such as Bangkok, Manila and Tianjin and between 10 and 20 meters in many other cities (UNESCO, 2012). The drop in groundwater levels often results in land subsidence, which can enhance hazard exposure due to coastal inundation and sea-level rise especially in settlements near the coast, and deterioration of groundwater quality. Cities susceptible to human-induced subsidence (mainly, developing country cities in deltaic regions with rapidly growing populations) could see significant increases in exposure (Nicholls *et al*., 2008).

Industry and Infrastructure. The impacts of climate change on industry include both direct impacts on industrial production and indirect impacts on industrial enterprises due to the implementation of mitigation activities (Li, 2008). The impact of climate change on infrastructure deterioration cannot be ignored, but can be addressed by changes to design procedures, including increases in cover thickness, improved quality of concrete, and coatings and barriers (Stewart *et al*., 2012). Climate change and extreme events may have a greater impact on large and medium-sized construction projects (Kim, 2007).

In July 2005, across Northwest India, the flooding affected an area of over 35,500 km^2, affecting 20 million people and causing economic damages of around US$3–5 billion (Swiss Re, 2006; Munich Re, 2006). Estimates suggest that by upgrading the drainage system in Mumbai, losses associated with a 1-in-100 year flood event today could be reduced by as much as 70%, and through extending insurance to 100% penetration, the indirect effects of flooding could be almost halved, speeding recovery significantly (Ranger, 2011). On the east coast of India, clusters of districts with poor infrastructure and demographic development are also the regions of maximum vulnerability, so extreme events are likely to be more catastrophic in nature for the people living in these districts. Moreover, the lower the district is in terms of the infrastructure index and its growth, the more exposed it is to the potential damage from extreme events and hence people living in these regions are likely to be highly vulnerable (Patnaik, 2009). In 2008, the embankments on the Kosi River (a tributary of the Ganges) failed and the channel shifted by as much as 120 km (Sinha, 2008), displacing over sixty thousand people in Nepal and three and a half million in India. Transport and power systems were disrupted across large areas. However, the embankment failure was not caused by an extreme event but represented a failure of interlinked physical and institutional infrastructure systems in an area characterized by complex social, political, and environmental relationships (Moench, 2010).

Climate change apparently has little influence on general travel decisions for tourism, even though weather extremes such as tropical storms are relevant, as revealed by a case study from Israel (Gossling and Hall, 2006). Tourist perceptions of weather and climate vary widely. Many Asian countries are major tourist destinations and more studies are needed to understand the impact of climate change on tourism. With respect to beach tourism, large

developing countries and small islands states may be among the most vulnerable due to high exposure and low adaptive capacity (Perch-Nielsen, 2010). A number of Asian countries were found vulnerable in this regard.

24.4.5.4. Vulnerabilities to Key Drivers

The impacts of climate change on human settlements, industry and infrastructure will not only be due to sea-level rise and extreme weather events. Disruption of basic services such as water supply, sanitation, energy provision, and transportation system have implications for local economies and "strip populations of their assets and livelihoods", in some cases leading to mass migration (UN-Habitat, 2010). Such impacts are not expected to be evenly spread among regions and cities, across sectors of the economy or among socioeconomic groups. They tend to reinforce existing inequalities and disrupt the social fabric of cities and exacerbate poverty.

A study of Chittagong, Bangladesh, concludes that urban adaptation and strengthening of local government capacity to reduce vulnerability of the urban poor is not considered a priority in national climate change adaptation policy (Ahammad, 2011). As a result, those most at risk from climate extremes are not given adequate attention. In addition, unequal access to education, health and other public services not only contribute to an increase in income disparities, but can also increase vulnerabilities to climate extremes. In the last two decades, 11 economies of Asia, accounting for more than four-fifths of the region's population, have experienced a widening gap between rich and poor (ADB, 2012). These development challenges can increase the impacts of climate extremes and undermine opportunities arising from adaptation.

Rapid economic growth in Asia is translating into land-use related changes, faster construction of buildings and infrastructure, and corresponding industrial development. While such development is improving the quality of life, it is also creating more impervious surfaces and thus increasing both the localized heat-island effect as well as flooding in dense urban environments. UN-Habitat (2010) states that "Climate change has direct effects on the physical infrastructure of a city – its network of buildings, roads, drainage, and energy systems – which in turn impact the welfare and livelihoods of its residents". The increasing frequency and intensity of extreme climatic events and slow-onset changes will increase the vulnerability of urban economic assets and subsequently the cost of doing business.

In northern Asia, thawing of permafrost can affect residential buildings, pavements, pipelines used to transport petroleum and gas, pump stations and extraction facilities. Ice roads, an important form of transportation for many northern activities may not be passable when permafrost thaws (Kelmelis, 2011; Smith, 2011; Forbes, 2011; FNCRF, 2010).

24.4.5.5. Adaptation Options

An ADB and UN report estimates that "about two-thirds of the $8 trillion needed for infrastructure investment in Asia and the Pacific between 2010 and 2020 will be in the form of new infrastructure, which creates tremendous opportunities to design, finance and manage more sustainable infrastructure" (ADB, 2012). A recent study estimated that direct and indirect losses for a 1-in-100 year flooding in Mumbai could triple by the 2080s compared with the present (increasing from US$700 to US$2,305 million), and suggests adaptation measures to reduce future damages (Ranger *et al.*, 2011). The massive investment required may not be affordable for most of the developing countries of Asia (Zevenbergen and Herath, 2008). Hallegatte *et al.* (2011) suggests that adaptation measures, especially in developing countries, offer a 'no regrets' solution "where basic urban infrastructure is often absent (e.g. appropriate drainage infrastructure), leaving room for actions that both increase immediate well-being and reduce vulnerability to future climate change". Adaptation measures, such as improvements to a city's drainage systems and extending insurance to 100% penetration, can reduce losses associated with a 1-in-100 year flood event by 50-70% (Ranger *et al.*, 2011).

The role of urban planning and urban planners in adaptation to climate change impacts has recently been emphasized (IPCC, 2012; Fuchs *et.al.*, 2011). City planners with greater understanding of climate change related

hazards and capable of communicating associated risks can effectively utilize spatial planning and social infrastructure as tools for adaptation in cities (Fuchs *et.al.*, 2011). Climate-sensitive urban planning is effective as a long-term adaptation measure if it takes into account climate variability, including uncertainty, and systems vulnerability and capacity (IPCC, 2012). Based on a review of governmental adaptation strategies in selected cities (including Ho Chi Minh City and Singapore in Asia), Birkmann *et al.* (2010) argue that a paradigm shift is needed in urban climate change adaptation, away from a focus on solely adapting physical infrastructure, towards also adapting planning, management and governance modes to be able to deal with the uncertainty and the unprecedented challenges implied by climate change. Garschagen and Kraas (2011) call for a stronger consideration of the multiple other challenges for urban governments in line with the comprehensive social, economic and political transformation underway in many of Asia's transition countries and emerging economies. Urban climate change adaptation in Asia cannot be debated without putting these debates into the context of these current and future transformations in the human domain. Institutional and cultural challenges can also emerge when transferring global concepts (e.g. on resilience) to Asia in order to guide the political processes around urban climate change adaptation. This is because the institutional set-up might limit the opportunity for implementing the respective management principles, for example on co-learning, self-organization or bottom-up decision making (Garschagen *et al.*, 2011). Paying particular attention to the national specifics, Revi (2008) suggests a framework for adapting Indian cities to climate change.

Climate change is expected to influence the demand for space cooling and heating (van Vuuren *et al.*, 2011). Air conditioning can reduce vulnerability to heat waves, but the extra energy demand will be in the range 750,000-1,350,000 GWh with a 3.7 °C increase in surface temperatures under different population scenarios and increasing incomes by the year 2100 (Akpinar-Ferranda and Singh, 2010). Green infrastructure has an important role in mitigating the impacts of climate change on urban areas, including reducing energy demand and improving stormwater management (Barber *et al.*, 2009; Gaffin *et al.*, 2012). Urban park systems, street trees, green roofs (Oberndorfer *et al.*, 2007), green walls, permeable pavements and other green infrastructure can improve urban climate and hydrology, while providing ecological and health co-benefits.

A tried method for adapting pavements, railroads, and oil and gas pipelines for the thawing of permafrost is thermal stabilization. Monitoring the buildings' basements and their timely stabilization is the main adaptation measure for residential and industrial buildings. Projected changes in permafrost should be considered by planners of new infrastructure, residential and industrial buildings. A key component of informing policy and decision-making is quantitative scientific research concerning past, present, and future permafrost changes and impacts (FNCRF, 2010; Anisimov *et al.*, 2010; Forbes *et al.*, 2011).

24.4.6. Human Health, Security, Livelihoods, and Poverty

24.4.6.1. Sub-Regional Diversity

Asia is predominantly an agrarian society as is evident from 58% of its total population living in rural areas, out of which 81.8% are dependent on agriculture for their livelihoods (FAOSTAT, 2011). In addition, agriculture employs 24.7% of the total population in these countries and contributes 15.3% of the total value-added GDP (FAOSTAT, 2011; World Bank, 2011). Asia also has high levels of rural poverty compared to urban poverty, with relatively higher poverty incidence in the eight least developing countries in the region (FAOSTAT, 2011). The high incidence of rural poverty and hunger is closely related to heavy dependence on natural resources that are directly influenced by changes in weather and climate, indicating a close connection between rural livelihoods and poverty (IFAD, 2010; Haggblade *et al.*, 2010).

Although Asia has emerged as an economic power during recent decades, there is still a considerable gap in progress in developmental indicators when compared to rest of the world (World Bank, 2011). In terms of these indicators, Southeast Asia is the third poorest region in the world after Sub-Saharan Africa and Southern Asia, and ranks poorly in terms of labor productivity, access to food, maternal health, and forestation (UN, 2009). Consequently, as a large proportion of rural populations depend on agriculture, agriculture has been identified as a key driver of economic growth in the region (World Bank, 2007).

Impacts on human security in Asia will primarily manifest through direct and indirect impacts on water resources, agriculture, coastal areas, resource-dependent livelihoods and on urban settlements and infrastructure, with implications for human health and well-being. To a large extent, regional disparities on account of socio-economic context and geographical characteristics among others, define the differential vulnerabilities and impacts within countries in Asia (Sivakumar and Stefanski 2011; Thomas, 2008).

24.4.6.2. Observed Impacts

Floods and health. Epidemics have been reported in the aftermath of floods and storms (Bagchi, 2007) due to decreased drinking water quality (Harris *et al*., 2008; Hashizume *et al*., 2008; Kazama *et al*., 2012; Solberg, 2010), proliferation of mosquitos (Pawar *et al*., 2008), exposure to rodent-borne pathogens like hantavirus and leptospira (Kawaguchi *et al*., 2008; Zhou *et al*., 2011) and to intermediate host snails of shistosoma (Wu *et al*., 2008). Contaminated flood waters in urban environments have caused exposure to pathogens and toxic compounds, as noted in for example India and Pakistan (Sohan *et al*., 2008; Warraich *et al*., 2011). Mental disorders and posttraumatic stress syndrome are also observed in disaster prone areas (Li *et al*., 2010; Udomratn, 2008), and have in India been linked to age and educational level (Telles *et al*., 2009).

Heat and health. The effects of heat on mortality and morbidity, mainly in terms of hospital admission, have been studied in many countries throughout Asia, with a specific focus on effects among the elderly and persons with cardiovascular and respiratory disorders (Guo *et al*., 2009; Huang *et al*., 2010; Kan *et al*., 2007). Associations between temperature rise and mortality have been shown for India, Thailand (McMichael *et al*., 2008) and several cities in East Asia, including Japan, South Korea, China and Taiwan (Chung *et al*., 2009; Kim *et al*., 2006). Several studies have analyzed the health effects of air pollution in combination with increased temperatures (Lee *et al*., 2007; Qian *et al*., 2010; Wong *et al*., 2010; Yi *et al*., 2010). Intense heat waves have also been shown to affect outdoor workers in South and East Asia (Hyatt *et al*., 2010; Nag *et al*., 2007).

Drought and health. Prolonged drought in combination with windy conditions increases the exposure to sand and dust, often mixed with toxic compounds (Wang *et al*., 2011d). There are indications that dust storms in South West, Central and East Asia increase hospital admissions and worsen asthmatic conditions, as well as causing skin and eye irritations (Griffin *et al*., 2007; Hashizume *et al*., 2010; Kan *et al*., 2012; Tam *et al*., 2012). Prolonged drought may also lead to wildfires and haze exposure, with increased morbidity and mortality, as observed in Southeast Asia (Johnston *et al*., 2012). Drought can also cause disruption of food security that leads to increases of malnutrition (Kumar *et al*., 2005), and consequently increase susceptibility to infectious diseases.

Water-borne diseases. Many pathogens and parasites multiply faster at higher temperatures. Increases in temperatures have been correlated with outbreaks of water-borne diseases in for example East Asia (Huang *et al*., 2008; Onozuka *et al*., 2010¸ Zhang *et al*., 2007). Other studies from South and East Asia have shown a correlation between diarrheal outbreaks and a combination of higher temperatures and heavy rainfall (Chou *et al*., 2010; Hashizume *et al*., 2007; Majra and Gur, 2009). Increasing coastal water temperatures have been correlated with outbreaks of systemic *Vibrio vulnificus* infection in Israel (Paz *et al*., 2007) and Taiwan (Kim and Jang, 2010). Cholera outbreaks in coastal populations in South Asia have been associated with increasing water temperatures and algal blooms (Huq *et al*., 2005). More distal climate modes, such as El Niño and the Indian Ocean Dipole, that arise from ocean-atmosphere interactions in the tropical Pacific and Indian Ocean, respectively, have been associated with cholera epidemics in Bangladesh (Pascual *et al*., 2000; Rodó *et al*., 2002; Hashizume *et al*., 2011)

Vector-borne diseases. Increasing temperatures affect vector-borne pathogens during the extrinsic incubation period and shorten the life-cycles of vectors, thereby facilitating larger vector populations and enhanced disease transmission, whilst vector's ability to acquire and maintain a parasite/pathogen tails off at higher temperatures (Paaijmans *et al*., 2012). Several Asian studies have focused on the emergence of dengue fever. Outbreaks have been correlated with temperature and rainfall with varying time lags (Sriprom *et al*., 2010; Hsieh and Chen 2009, Nitatpattana *et al*., 2008; Shang *et al*., 2010; Su, 2008; Hii *et al*., 2009; Hashizume *et al*., 2012). Outbreaks of the vaccine-preventable Japanese encephalitis have been linked to rainfall in studies from the Himalayan region (Bhattachan *et al*., 2009; Patridge *et al*., 2007), and to a combination of rainfall and temperatures in South and East

Asia (Bi *et al*., 2007; Murty *et al*., 2010). Malaria prevalence is often influenced by other factors than climate variability, but studies from India and Nepal have found correlations with rainfall (Dahal, 2008; Dev and Dash, 2007; Devi and Jauhari, 2006; Laneri *et al*., 2010), whereas temperature was linked to malaria distribution and seasonality in Saudi Arabia (Kheir *et al*., 2010). The re-emergence of malaria in central China has been attributed to rainfall and increases in temperature close to water bodies (Zhou *et al*., 2010). Temperature, precipitation, and the virus-carrying index among rodents have been found to be correlated with the prevalence of hemorrhagic fever with renal syndrome in China (Guan *et al*., 2009; Yan *et al*., 2008).

Livelihoods and Poverty. There have been significant changes in terms of livelihood diversification in Asia over recent decades due to rapid economic development (see Table 24-5). Estimates suggest that currently about 51% of total income in rural Asia comes from non-farm sources (Haggblade *et al*., 2010; Haggblade *et al*., 2009), out of which a major proportion comes from local non-farm business and employment. There has also been steady growth in the proportion of remittances contributing to rural income (Estudillo and Otsuka, 2010). Asia has made significant improvements in poverty eradication over the past decade (World Bank, 2008). At the subregional level, East Asia has recorded a rapid reduction in poverty, followed by South Asia (IFAD, 2010). A significant part of the reduction has come from population shifts, rapid growth in agriculture, and urban contributions (Janvry and Sadoulet, 2010). Literature suggests that climate change negatively impacts livelihoods (see Table 24-5) and that these impacts are directly related to natural resources affected by changes in weather and climate. One of the important factors to be considered while evaluating the past impacts of climate change on agriculture is the play of several factors that have made the region's agriculture less sustainable, which include input non-responsive yields, soil erosion, natural calamities, and water and land quality related problems (Dev, 2011). These factors have predisposed the region's livelihoods to climate change vulnerability. Rural livelihoods are more severely impacted than the urban ones due to the predominantly agricultural population and the poor are more vulnerable to livelihood loss.

24.4.6.3. Projected Impacts

Health effects. An emerging interregional public health concern in Asia is increasing mortality and morbidity due to heat waves. An ageing population in Asia will increase the number of people at risk, especially those with cardio-vascular and respiratory disorders. The rapid urbanization and growth of megacities in Asia add to the magnitude of the problem with the urban heat island effect that may increase downtown temperatures considerably compared to surrounding rural areas (Tan *et al*., 2010), even though local adaptation of the built environment and urban planning will define the magnitude of the impacts on public health. The relationship between temperature and mortality often shows a U-shaped curve (Guo *et al*., 2009). Studies from both tropical and temperate environments in Asia show increased mortality in particular in rural environments during cold events, even if temperatures do not fall below 0°C (Hashizume *et al*., 2009; Wu *et al*., 2011). However, some studies on cold-related deaths in developing areas suggest that other factors than climate are important contributors here, and that climate change will not decrease cold-related deaths to any larger extent in such environments (Honda and Ono 2009). Heat stress disorders and consequent productivity loss among workers have also been reported in Asia (Lin *et al*., 2009; Langkulsen *et al*., 2010).

Climate change will affect the local transmission of many climate-sensitive diseases. Increases in heavy rain and temperature are projected to increase the risk of diarrhoeal diseases in for example China (Zhang *et al*., 2008). The impact of climate change on malaria risk will differ between areas, as projected for West and South Asia (Husain and Chaudhary, 2008; Garg *et al*., 2009; Majra and Gur, 2009), whilst a study reported that the impact of socio-economic development is larger than that of climate change (Béguin *et al*., 2011). Some studies have developed climate change-disease prevalence models, for example one for schistosomiasis in China shows an increased northern distribution range of the disease with climate change (Kan *et al*., 2012, Zhou *et al*., 2008). Impacts of climate change on fish production (Qiu *et al*., 2010) is being studied, along with impacts on chemical pathways in the marine environment and consequent impacts on food safety (Tirado *et al*., 2010b), including seafood safety (Marques *et al*., 2010).

Livelihood and Poverty. Floods, droughts and changes in seasonal rainfall patterns are expected to negatively impact crop yields, food security and livelihood in vulnerable areas (Dawe *et al*., 2008; Douglas, 2009; Kelkar *et al*.,

2008). Rural poverty in parts of Asia could be exacerbated (Skoufias et al., 2011) due to negative climate change impacts on the rice crop and increases in food prices and the cost of living (Hertel et al., 2010; Rosegrant, 2011). The poverty impacts of climate change would be heterogeneous among countries and social groups (see Table 24-6). In a low crop productivity scenario, food exporting countries, such as Indonesia, the Philippines and Thailand, would benefit from climate change related global food price rises and be able to reduce poverty, while countries such as Bangladesh would experience a net increase in poverty of 15% by 2030 (Hertel et al., 2010). Regression analyses conducted by Skoufias *et al.* (2011) indicate significant negative impacts of a shortfall in rainfall on the welfare of rice farmers in Indonesia, compared to a delay in the onset of rainfall. These impacts may lead to global mass migration and related conflicts (Laczko and Aghazarm, 2009; Barnett and Webber, 2010; Warner, 2010; World Bank, 2010). Climate-driven changes in tundra and forest-tundra biomes can influence indigenous peoples of the North Asia due to their traditional livelihood: nomadic tundra pastoralism, fishing and hunting (Kumpula *et al.*, 2011).

24.4.6.4. Vulnerabilities to Key Drivers

Key vulnerabilities vary widely within the region. Climate change can exacerbate current socio-economic and political disparities and add to the vulnerability of Southeast Asia and Central Asia to security threats that may be transnational in nature (Jasparro and Taylor, 2008; Lioubimtseva and Henebry, 2009). Apart from detrimental impacts of extreme events, vulnerability of livelihoods in agrarian communities also arises from geographic settings, demographic trends, socio-economic factors, access to resources and markets, unsustainable water consumption, farming practices and lack of capacity to adapt (Mulligan *et al.*, 2011; Acosta-Michlik and Espaldon, 2008; Allison *et al.*, 2009; Knox *et al.*, 2011; Lioubimtseva and Henebry, 2009; Byg and Salick, 2009; Salick and Ross, 2009; Salick *et al.*, 2009; Xu *et al.*, 2009; Winters *et al.*, 2009; UN, 2009). Urban wage labourers were found to be more vulnerable to cost of living related poverty impacts of climate change than those who directly depend on agriculture for their livelihoods (Hertel *et al.*, 2010). In Southeast Asia, an important topic of focus is forests and fires; for example the vulnerability of agriculture, forestry and human settlements on peatland areas in Indonesia (Murdiyarso and Lebel, 2007). Human health is also a major area of focus for Asia (Munslow and O'Dempseya, 2010), where the magnitude and type of health effects from climate change will differ within Asia depending on differences in socio-economic and demographic factors, health systems, the natural and built environment, land use changes, and migration in relation to local resilience and adaptive capacity. The role of institutions is also critical, particularly in influencing vulnerabilities arising from social heterogeneity based on gender (Ahmed and Fajber, 2009), caste and ethnic differences (Jones and Boyd, 2011), and securing climate-sensitive livelihoods in rural areas (Agrawal and Perin, 2008).

24.4.6.5. Adaptation Options

Cross-sectorial collaborations will be needed for the development of sustainable adaptive measures with interactions between the health sector and disaster preparedness programs, water management, sanitation, urban planning, the food industry and the animal health sector. Disaster preparedness on a local community level could include a combination of indigenous coping strategies, early-warning systems, and adaptive measures (Paul and Routray, 2010). Heat warning systems have been shown to be successful in preventing deaths among risk groups, as in Shanghai (Tan *et al.*, 2007). Also proven successful is the implementation of new work practices to avoid heat stress among outdoor workers, as shown in studies from Japan and the UAE (Joubert *et al.*, 2011; Morioka *et al.*, 2006). As described in section 24.7, there are many win-win solutions for public health from the interaction of adaptation and mitigation measures that involve urban environments and air pollution. Early warning models have been developed for haze exposure from wildfires, in for example Thailand (Kim Oanh and Leelasakultum, 2011). Early warning models are also being tested in infectious disease prevention and vector control programs, as for malaria in Bhutan (Wangdi *et al.*, 2010) and Iran (Haghdoost *et al.*, 2008), or are being developed, as for dengue fever region-wide (Wilder-Smith *et al.,* 2012).

The available literature suggests a need for identifying and promoting technologies and policy options that will provide both mitigation potential and sustained income generation potential in a changed climate (Bhandari *et al.*,

2007; Rosenzweig and Tubiello, 2007; Paul *et al*., 2009a). Interesting examples seem to emerge on how some practices provide completely unexpected livelihood benefits which otherwise may not be captured in standard evaluation frameworks, as in the case of the introduction of traditional flood mitigation measures in China which could positively impact the local livelihoods, leading to reductions in both the physical and economic vulnerabilities of communities (Xu *et al*., 2009). A significant amount of literature has stressed the greater role of local communities in decision making (Alauddin and Quiggin, 2008) and in prioritization and adoption of adaptation options (Prabhakar *et al*., 2010; Prabhakar and Srinivasan, 2011). Defining adequate community property rights, including solving issues such as land tenure, reducing income disparity, exploring market-based and diversified off-farm livelihood options, moving from production-based approaches to productivity and efficiency decision-making based approaches, and promoting integrated decision-making approaches, have been suggested (Merrey *et al*., 2005; Brouwer *et al*., 2007; Paul *et al*., 2009; Niino, 2011; Stucki and Smith, 2011).

Climate resilient livelihoods can be fostered through the creation of a bundle of capitals (natural, physical, human, financial and social capital) and poverty eradication (see Table 24-8). In general, greater emphasis on agricultural growth has been suggested as an effective means of reducing rural poverty (Janvry and Sadoulet, 2010; Rosegrant, 2011). Bundled approaches are known to facilitate better adaptation than individual adaptation options (Acosta-Michlik and Espaldon, 2008; Fleischer *et al*., 2011). Community-based approaches, as against top-down interventions, have been suggested to identify adaptation options that address poverty and livelihoods, as these techniques help capture information at the grassroots (Aalst *et al*., 2008), and help integration of disaster risk reduction, development, and climate change adaptation (Heltberg *et al*., 2010), connect local communities and outsiders (Aalst *et al*., 2008), and address the location-specific nature of adaptation (Iwasaki *et al*., 2009; Rosegrant, 2011). Some groups can become more vulnerable to changes after being 'locked into' specialized livelihood patterns as shown in the case of fish farmers in India (Coulthard, 2008).

[INSERT TABLE 24-8 HERE
Table 24-8: Summary of adaptation options for securing livelihoods in Asia.]

24.4.7 Valuation of Impacts and Adaptation

Research on the valuation of climate change impacts and adaptation in Asia has been highly limited. However, recently there is growing research attention to the assessment of the aggregate costs of climate change impacts and adaptation. For instance, in Bangladesh, by 2050, the total adaptation cost is estimated at US$5.7 billion to offset the added inundation from climate change, including US$3.3 billion to protect infrastructure, such as roads, railways, river embankments, and drainage from inland monsoon floods, and US$2.4 billion for storm-surge protection (World Bank, 2011). There are a few studies focusing on dispersed sectors though without comprehensive economic valuation of the costs and benefits of adaptation. Examples of such studies include exploring low-cost adaptation strategies for reducing the net vulnerability of sorghum production systems in India (Srivastava *et al*., 2010); assessing vulnerability and adaptation of agriculture and food security, water resources and human health in Central Asia (Lioubimtseva and Henebry, 2009); socio-economic impacts of drought and flood in South Asia (Muhammed *et al*., 2007); investigation of vulnerability and adaptive capacity to climate variability and water stress in the Lakhwar watershed in Uttarakhand State, India (Kelkar *et al*., 2008); assessing socio-economic vulnerability and adaptation measures in West Coast of Peninsular Malaysia (Drainage and Irrigation Department, 2007); and simulating impacts on rice yields in a number of Asian countries (Matthews *et al*. 1997). In addition to changes in temperature and rainfall, changes in the frequency of extreme climatic events could be damaging and costly to agriculture (Aydinalp and Cresser, 2008; Muhammed *et al*., 2007; Su *et al*., 2009).

A study of the economics of climate change in Southeast Asia with a focus on Indonesia, the Philippines, Thailand, and Vietnam (ADB, 2009) reported that many of the impacts from climate change are not in traditional economic sectors such as agriculture, including fisheries and aquaculture, forestry and mining, with the result that their valuations are difficult with uncertainly and incomplete information. Furthermore, some of the economic and social valuations, such as loss of life or damage to ecosystems, can be contentious. Without further mitigation or adaptation (under the A2 scenario), the PAGE2002 integrated assessment model projects for the four countries to suffer a mean loss of 2.2% of gross domestic product (GDP) by 2100 on an annual basis, if only the market impact

(mainly related to agriculture and coastal zones) is considered. This is well above the world's mean GDP loss of 0.6% each year by 2100 due to market impact alone. In addition, the mean cost for the four ASEAN countries by 2100 could reach 5.7% of the GDP if non-market impacts related to health and ecosystems are included and 6.7% of the GDP if catastrophic risks are also taken into account.

The PAGE2002 model also found that the cost of adaptation for agriculture and coastal zones (mainly the development of drought- and heat-resistant crops and the construction of sea walls) would be about $5 billion/year by 2020 on average, and that this investment would be paid back in the future. For instance, the annual benefit of avoided damage from climate change is expected to exceed the annual cost by 2060 and, by 2100, benefits could reach 1.9% of GDP, compared to the cost at 0.2% of GDP, with the results at mean and 5% probability level under the A2 scenario. This shows that the benefits from adaptation are projected to outweigh the costs of implementing adaptation measures in the long term. It was also stressed that there are currently great uncertainties associated with the economic aspects of climate change (ADB, 2009). Adaptation cannot entirely remove the projected damage of climate change, and thus must be complemented with global mitigation of CO_2 in order to avoid the greater impact of future climate change (Begum *et al*., 2011; ADB, 2009; MNRE, 2010).

24.5. Adaptation and Managing Risks

24.5.1. Conservation of Natural Resources

Even without climate change, natural resources are already under severe pressure in most of East, Southeast, and South Asia, as well as in much of Central and West Asia, and parts of North Asia and the Tibetan Plateau. The extraordinarily high rates of deforestation and forest degradation in Southeast Asia have received most attention (Sodhi *et al*., 2010; Miettinen *et al*., 2011), but ecosystem degradation, with the resulting loss of natural goods and services, is also a major problem in other forest types and in non-forest ecosystems. These pressures result from rising populations and rapid economic development, exacerbated by poor governance and the low priority of natural resource conservation. The impacts of projected climate change are expected to intensify these pressures in most areas, but the relative importance of climate and non-climate stressors is difficult to predict in most cases. Coral reefs are an exception, with climate change and ocean acidification a clear threat to all reefs in the region and thus the millions of people who depend on them (Hoegh-Guldberg, 2011; Burke *et al*., 2011; see also Chapter 30, this volume).

With natural resource conservation already under stress, the focus has been on actions that would be beneficial even without climate change, including minimizing non-climate pressures on natural resources and restoring connectivity to allow movements of genes and species between fragmented populations (Lindenmayer *et al*., 2010). Authors have also suggested a need to identify and prioritize for protection areas that will be subject to the least damaging climate change ('climate refugia') and to identify additions to the protected area network that will allow for expected range shifts, for example by extending existing protected areas to higher altitudes or latitudes (Hannah, 2010; Hole *et al*., 2011; Shoo *et al*., 2011). Moving beyond this focus on wild species and ecosystems, ecosystem-based approaches to adaptation aim to use the resilience of natural systems to buffer human systems against climate change, with potential social, economic and cultural co-benefits for local communities (see Box CC-EA: Ecosystem-based approaches to adaptation – emerging opportunities).

24.5.2. Flood Risks and Coastal Inundation

Many coasts in Asia are exposed to extreme weather, as well as more gradual changes in climate and sea level, and are accordingly anticipated to face threats from floods and coastal inundation. Responding to a large number of climate change impact studies for each country over the past decade (e.g. Karim and Mimura, 2008; Pal and Al-Tabbaa, 2009; World Bank, 2010), various downscaled tools to support, formulate and implement climate change adaptation policy for local governments are under development. One of the major tools is vulnerability assessment and policy option identification with Geographical Information Systems (GIS). These tools have been developed for flood risk management so far, and most give consideration in varying degrees to climate change impacts, such as

long-term rises in sea-level. These tools are expected to be of assistance in examining city-specific solutions in response to city-specific impacts characterized by distinct climatic, hydrological and socioeconomic features, and in building the adaptation capacity of stakeholders in the community as a result.

These tools and systems sometimes take community-based approaches. The background to these is as follows: vulnerability and exposure to climate change at the coast is exacerbated by population growth, socio-economic growth and urbanization, however assessments of vulnerabilities have uncertainties and limitations and do not necessarily provide suitable information for local stakeholders to take appropriate action at the local level. Therefore bottom-up approaches are potentially more effective in building adaptive capacity by involving local stakeholders (Van Aalst *et al*., 2008). As local stakeholders have different sets of understanding, conflict assessment is needed to plan and implement adaptation policy (e.g. Baba *et al*., 2012). Also, community-based approaches may have a limitation in that they place greater responsibility on the shoulders of local people without necessarily increasing their capacity proportionately (Allen, 2006). As the nature of adaptive capacity varies, depending on the formulation of social capital and institutional context in the local community, it is essential for the approaches to have an understanding of local community structures (Adger, 2003). If the approaches satisfy these conditions, flood risks and coastal inundation exacerbated by climate change would be perceived as issues for the current generation and adaptation policy would be better understood by local stakeholders.

24.5.3. Economic Growth and Equitable Development

Economic, social, and environmental equity is an enduring challenge in many parts of Asia. Generally, the level of wealth (typically GDP) has been used as a measure of human vulnerability of a country or region, but this approach has serious limitations (Mattoo and Subramanian, 2012; Dellink *et al*., 2009; Bosetti and Frankel, 2009). In many cases, social capital, an indicator of equity in income distribution within countries, is a more important factor in vulnerability and resilience than GDP per capita (Lioubimtseva and Henebry, 2009; Islam *et al*., 2006). Furthermore, political and institutional instabilities can undermine the influence of economic development (Lioubimtseva and Henebry, 2009). Poor and vulnerable countries are at greater risk from the impacts of climate extremes as their options for coping which such events are limited. This is particularly true for developing countries in Asia with a high level of natural resource dependency. Provision of adequate resources based on the burden sharing and the equity principle will serve to strengthen appropriate adaptation policies and measures in such countries (Su *et al*., 2009). Mainstreaming adaptation into government's sustainable development policy portrays a potential opportunity for good practice to build resilience and reduce vulnerability, depending on effective, equitable and legitimate actions to overcome barriers and limits to adaptation (Lioubimtseva and Henebry, 2009; Agrawala and van Aalst, 2005; Lim *et al*., 2005; ADB, 2005). It requires growth with economic stability, development with social equity and poverty eradication, and the continued functioning of ecosystems as life support systems to sustain development.

24.5.4. Mainstreaming and Institutional Barriers

The level of climate change adaptation mainstreaming is most advanced in the context of official development assistance, where donor agencies and international financial institutions have made significant steps towards taking climate change adaptation into account in their loan and grant making processes (Gigli and Agrawala, 2007; Klein *et al*., 2007b). In contrast, within developing countries, actual projects on the ground to mainstream adaptation to climate change remain limited and significant institutional and cognitive barriers remain (Yohe *et al*., 2007; Gigli and Agrawala, 2007). For example, in the Philippines, the factors that hinder climate change mainstreaming include: national priorities that are geared towards what are perceived to be more pressing concerns, such as employment generation and education, and a pervasive lack of awareness of the impacts of climate change on sustainable development (Lasco *et al*., 2009). However, there are massive investments in infrastructure projects designed to adapt to weather-related hazards. Local government units could play a crucial role, as shown by the experience of Albay province in the Philippines which pioneered climate action at the grassroots level (Lasco *et al*., 2012)

While some practical experiences of adaptation in Asia at the regional, national and local level are emerging, there can be barriers that impede or limit adaptation. These can include lack of financial resources for adaptation implementation, institutional barriers, biophysical limits to ecosystem adaptation and others (Moser and Ekstrom, 2010). Regional adaptation strategies are necessary to tackle issues such as food security. There are already some groups, such as the Association of South East Asian Nations (ASEAN), but there is a need for global and regional strategic partnerships in this regard (Singleton *et al*., 2010). The success of deployment, implementation and sustainability of adaptation options can be influenced by the political economy of the region. Issues with resource availability might not only result from climate change, but also from weak governance mechanisms and the breakdown of policy and regulatory structures, especially with common-pool resources (Moser and Ekstrom, 2010). Furthermore, the impact of climate change depends on the inherent vulnerability of the socio-ecological systems in a region as much as on the magnitude of the change (Evans, 2010). Recent studies linking climate-related resource scarcities and conflict call for enhanced regional cooperation (Gautam, 2012).

24.5.5. Role of Higher Education in Adaptation and Risk Management

To enhance the development of young professionals in the field of climate change adaptation, it is of utmost importance to include the topic in higher education, especially in formal education programs. Shaw *et al*. (2011) emphasized the need for higher education in adaptation and disaster risk reduction in the Asia-Pacific region through: environment disaster linkage, focus on hydro-meteorological disasters, and emphasizing synergy issues between adaptation and risk reduction. Similar needs have also been highlighted by Ryan *et al*. (2010), Nomura and Abe (2010), Chhokar (2010) and Niu *et al*. (2010). Higher education should be done through lectures and course work, field studies, internships, and establishing education-research linkages by exposing the students to field realities. In this regard, guiding principles could include: an inclusive curriculum, a theoretical focus, field orientation, multi-disciplinary courses and practical skill enhancement. Bi-lateral or multi-lateral practical research programs on adaptation and risk management by the graduate students and young faculty members would expose them to the real field problems.

24.6. Adaptation and Mitigation Interactions

Climate change mitigation benefits climate change adaptation in Asia by increasing the prospects that adaptation can address many unavoidable impacts, and adaptation benefits mitigation by somewhat moderating the impacts of particular GHG concentration levels due to reduced sensitivities or increased coping capacities. One of the most prominent examples is increasing the efficiency and affordability of air conditioning, which would extend space conditioning benefits to a larger share of populations with rising standards of living, while at the same time reducing carbon emissions associated with electricity generation. Other examples include the development of sustainable cities in Asia with less fossil fuel driven vehicles (mitigation) and with more trees and greenery (carbon storage as well as adaptation to the urban heat island effect), which would have a number of co-benefits including public health – a promising strategy for “triple win” interventions (Romero-Lankao *et al*., 2011). A further example is China’s leadership in promoting solar energy technologies, where reduced requirements for carbon-based electricity generation are combined with technological change, job creation, and skill development that enhance adaptive capacities.

Other possible synergies (and/or conflicts) tend to be more subtle. In general, integrated mitigation and adaptation responses tend to focus on either land-use changes, often involving ecosystem functions, or on technology development and use. For instance, changes in land use, such as agroforestry, may provide both mitigation and adaptation benefits (Verchot *et al*., 2007), or otherwise depending on how they are implemented. Agroforestry practices will provide carbon storage and may at the same time decrease soil erosion, increase the resilience against floods, landslides and drought, increase soil organic matter, reduce the financial impact of crop failure, as well as have biodiversity benefits over other forms of agriculture as shown, for example, in Indonesia (Clough *et al*., 2011). Integrated approaches are often needed when developing mitigation-adaptation synergies, as seen in waste-to-compost projects in Bangladesh (Ayers and Huq, 2009). Linking adaptation to mitigation makes mitigation action more relevant for many low-income regions.

In addition to agroforestry, any ecological adaptation measures that increase plant biomass and/or soil carbon content, such as ecosystem protection and reforestation, will contribute to climate mitigation by carbon sequestration. However, exotic monocultures may fix more carbon than native species mixtures while supporting less biodiversity and contributing less to ecological services. Compromises that favor biodiversity-rich carbon storage that is resilient to future climate change may be necessary (Díaz *et al*., 2009). The potential for both adaptation and mitigation through forest restoration is greatest in the tropics (Sasaki *et al*., 2011). At higher latitudes (>45ºN), reforestation can have a net warming influence by reducing surface albedo (Anderson-Teixeira *et al*., 2012). The expansion of biofuel crops on abandoned and marginal agricultural lands could potentially make a large contribution to the mitigation of global carbon emissions, but could also have large negative consequences for both carbon emissions and biodiversity if it results directly or indirectly in the conversion of carbon-rich natural ecosystems to cropland (Fargione *et al*., 2010; Qin *et al*., 2011). Mechanisms, such as REDD+, that put an economic price on land-use emissions could reduce the risks of these negative consequences from biofuel expansion (Thomson *et al*., 2010), but the incentive structures need to be worked out very carefully (Busch *et al*., 2012).

There has also been an emphasis on forests and their management for providing resilient livelihoods and reducing poverty (Persha *et al*., 2010; Larson, 2011; Noordwijk, 2010; Chhatre and Agrawal, 2009). Securing rights to resources was found to be essential for greater livelihood benefits to the poor indigenous and traditional people (Macchi et al., 2008). Because of this, the need for REDD+ schemes to respect and promote community forest tenure rights has been emphasized (Angelsen, 2009). It has also been suggested that indigenous people can provide a bridge between biodiversity protection and climate change adaptation (Salick, 2009), which appears to be missing in the current discourse on ecosystems based adaptation. However, there are arguments against REDD+ supporting poverty reduction due to its inability to promote productive use of forests, which may keep communities in perpetual poverty (Campbell, 2009).

On rivers and coasts, the use of hard defenses (e.g. sea-walls, channelization, bunds, dams) to protect agriculture and human settlements from flooding may have negative consequences for both natural ecosystems and carbon sequestration by preventing natural adjustments to changing conditions. Conversely, setting aside landward buffer zones along coasts and rivers would be positive for both (Erwin, 2009), although this will often be difficult in practice. The very high carbon sequestration potential of the organic-rich soils in mangroves (Donato *et al*., 2011) and peatswamp forests (Page *et al*., 2011) provides opportunities for combining adaptation with mitigation through restoration of degraded areas.

Several mitigation technologies and measures will have public health benefits, such as controlled composting, state-of-the-art incineration, expanded sanitation coverage, and waste water management (Bogner *et al*., 2008). There are potentially large benefits for both public health and other sectors from climate change mitigation policies that reduce exposure to outdoor and indoor air-pollution (Haines *et al*., 2009). Decarbonizing electricity production efforts in India and China are projected to decrease mortality due to reduced PM5 and PM2.5 particulate matters (Markandya *et al*., 2009). Mitigation policies to reduce fossil fuel vehicles will increase air quality and decrease the health burden, particularly in urban environments as projected in India (Woodcock *et al*., 2009). The use of more public transportation, as well as increased walking and cycling, and fewer private cars could also improve public health (Woodcock *et al*., 2007). Abandoning the use of biomass fuel or coal for in-door cooking and domestic heating would substantially increase indoor air quality and respiratory and cardiac health among, in particular, women and children in India and China (Wilkinson *et al*., 2009). In reverse, actions to reduce current environmental-public health issues may often as an additional bonus have beneficial mitigation effects, like traffic emissions reduction programs in China (Wu *et al*., 2011) and India (Reynolds and Kandlikar, 2008). At the same time, climate change adaptation technologies, such as improved stormwater and wastewater management, can reduce electricity requirements for water pumping and water treatment; and advances in information, communication, and control technologies can contribute to both adaptation and mitigation efforts. Among financial means, low-risk liquidity options such as microfinance programs and risk transfer products can help lift the rural poor from poverty and accumulate assets (Barret *et al*., 2007; Jarvis *et al*., 2011).

24.7. Intra-regional and Inter-regional Issues

24.7.1. Trans-boundary pollution

Many Asian countries and regions face long-distance and trans-boundary air pollution problems. In eastern China, Japan and the Republic of Korea, these include dust storms that originate in the arid and semi-arid regions upwind, with impacts on climate, human health and ecosystems (Huang *et al.*, 2013). The susceptibility of the land surface to wind erosion is strongly influenced by vegetation cover, which is in turn sensitive to climate change and other human impacts. In the humid tropics of Southeast Asia, in contrast, the major trans-boundary pollution issue involves smoke aerosols from burning of biomass and peatlands [24.9.2], mostly during clearance for agriculture. Apart from the large impact on human health, these aerosols may be having a significant effect on rainfall in equatorial regions, leading to the possibility of climate-feedbacks, with fires reducing rainfall and promoting further fires (Tosca et al., 2012; WG1 AR5 SOD Ch. 7). Pollutants of industrial origin are also a huge problem in many parts of the region, with well-documented impacts on human health [24.4.6] and the climate [WG1 AR5 SOD Ch. 7 and 8].

24.7.2. Trade and Economy

A well-functioning international trading system can help support adaptation to the challenges of climate change. Hence welfare gains from reforms to trade policies may be greater than normally measured if they also reduce GHG emissions globally (Huang *et al.*, 2011). In recent years, there has been a growing interest in the environmental impacts of regional trade liberalization. A study by Gumilang *et al.* (2011) suggests that overall AFTA (ASEAN Free Trade Agreement) has had a greater impact on the Indonesian economy than IJEPA (Indonesia–Japan Economic Partnership Agreement), while the adoption of both agreements contributes to increasing CO_2 emissions by 0.47% compared to the business-as-usual case. This is mainly due to the high emission coefficient of the transportation sector. On the other hand, the agreements did have a positive impact on water pollution indicators.

China's high economic growth and flourishing domestic and international trade has resulted in increased consumption and pollution of water resources. For instance, Guan and Hubacek (2007) found that North China, as a water scarce region, effectively exports about 5% of its total available freshwater resources, while accepting large amounts of wastewater from other regions' consumption. By contrast, South China, a region with abundant water resources, is effectively importing water from other regions, while their imports are creating wastewater polluting other regions' ecosystems.

24.7.3. Migration and Population Displacement

There is an emerging body of literature suggesting growing nexus between migration and climate change (International Organization for Migration, 2008; Piguet *et al.*, 2011). The global report of Internal Displacement Monitoring Center (2011) enlists climate related natural hazards such as floods and droughts as some of predominant causes for internal displacement. In 2010 alone, 38.8 million people were internally displaced 85% of them were due to hydrological hazards and 77% of displacements took place in Asia alone. Rapid-onset environmental changes such as floods are increasingly playing a role in migration in the case of Mekong Delta (Warner, 2010). Migration has also received attention in the literature as an adaptation option (Reuveny, 2007; Warner, 2010; ADB, 2012; The Government Office for Science, 2011). While some form of environmentally induced migration may be adaptive, other forms of environmental migration may indicate a failure of social-ecological systems to adapt (Warner, 2010), suggesting need for differentiating the root cause of migration and treating them through new forms of governance that connects the migrants with those who returned and remained.

Migration has become one of the strategies to sustain livelihoods in the wake of climate and environmental change (Barnett and Webber, 2010). The shift towards non-farm income activities, including migration, appears to be more prominent in countries and communities with least access to land (Winters *et al.*, 2009) and in those communities with better access to education (Estudillo and Otsuka, 2010). Increasing migration has led to increasing migration-

induced remittances contributing to Asian economies and decreased the poverty gap, but had negligible effect on the poverty rate (Vargas-Silva *et al*., 2009).

Migration could have negative impacts on the migrants as observed in the case of Bangladesh where migrant workers had to live and work under poor conditions such as crowded shelters, poor sanitation, conflict and competition with local population, and exploitation (Penning-Rowsell *et al*., 2011). Though forced migration can result from implementing some adaptation options such as construction of dams, the negative outcome from these migrations could be overcome by putting in place proper safeguards (The Government Office for Science, 2011). The most favorable approach is to deal with migration within a development framework and by incorporating into adaptation strategies (ADB, 2012; The Government Office for Science, 2011). Only such inclusive approach would make difference in whether climate induced migration would emerge as forced displacement or planned and facilitated adaptation strategy.

24.8. Research and Data Gaps

There are still regions within Asia that are not sufficiently represented in studies of observed climate change and its impacts, in particular Central and West Asia. Also, numerical data on trends in precipitation is hard to find compared to trends in temperature. Furthermore, research data on changes in extreme climate events does not cover most Asian regions. For freshwater resources studies, research priorities are as follows: (1) to increase the knowledge of future rainfall changes in regions by model ensembles to provide a better idea of future water supply, (2) to develop water management strategies across scales to adapt future changes in water demand and supply associated with climate change, (3) to elaborate more studies on successful water saving technologies and other adaptation options.

Scientific understanding of the impacts of climate change on ecosystems and biodiversity in Asia is currently limited by the poor quality and low accessibility of biodiversity information (GEO-5 Assessment Report, 2012). National biodiversity inventories are incomplete and very few sites have the accurate baseline information needed to identify changes brought about by climatic trends and other stressors. Quantitative information for sites in protected areas where non-climate impacts are minimized will be particularly valuable in the future. New and old data need to be digitized and made available on-line. Current warming projections suggest that large areas in the Asian tropical lowlands will experience climates in 2100 that have not existed anywhere on Earth for several million years (García-López and Allué, 2012). This novelty makes reliance on extrapolation from our current, limited, understanding of climatic controls on biological processes dangerous, and underlines the need for new research. Key priorities include the temperature dependence of carbon fixation by tropical trees and the thermal tolerance and acclimation capacity of both plants and animals (Corlett, 2011).

Boreal forest dynamics will be influenced by complex interactions between rising temperatures and CO_2 concentrations, permafrost thawing, forest fires, and insect outbreaks (Osawa *et al*., 2010; Zhang *et al*., 2011b). Understanding this complexity will require enhanced monitoring of biodiversity and especially of species ranges, improved modeling, and a greater knowledge of species biology (Anisimov *et al*., 2008). Long-term monitoring of biome boundary shifts and vegetation change is also needed because of slow rate of these changes. In remote and inaccessible areas such monitoring has been provided since 1978 by broad-swath satellite remote sensing data, however lack of coincidence in estimates of vegetation vigor provided by remote sensing techniques and by vegetation models requires further research and inter-calibration of methods (Xu *et al*., 2012).

There are still many gaps in our understanding of climate change impacts and vulnerabilities in the agricultural sector as well as appropriate adaptation options. The most studied crop is rice but there are still significant uncertainties in terms of accuracy of models, effect of CO_2 fertilization, and regional effects (Shuang-He *et al*., 2011; Zhang *et al*., 2010; Masutomi *et al*., 2009). For other crops, there is even greater uncertainty in terms of magnitude and direction of impacts of rising temperatures, precipitation changes, and CO_2 fertilization.

There is a need to increase knowledge of heat and air pollution interactions and health effects in different risk groups, in both urban and rural environments. There are research gaps in climate change impacts on children's

health in different socioeconomic and regional context to fill in. More trans-disciplinary research is needed on direct and indirect health effects from climate change impacts on water quality and quantity in different parts of Asia. Studies on social-economic and institutional dimension should also be given priority. For example, the impacts of climate change on women and their role in climate change adaptation needs to be investigated (Mula *et al*., 2010). There is also a need to identify low cost adaptation options and a need for scaling up of the same, considering the majority of population lives below the poverty line in some of the least developed countries. Greater understanding of various existing policy processes in place-specific geographic context, their compatibilities and non-compatibilities, is also needed. For example, interventions to increase livelihood options through conservation initiatives that may restrict access to natural resources for the very people that rely upon them for their living might make them more vulnerable (Roman and McEvoy, 2010). Research on adaptation and mitigation interactions that promotes sustainable development should be increased, as well as research on possible economic gains from different adaptation-mitigation strategies and measures.

More focused research will support the tackling of climate change impacts, vulnerability and adaptation in urban settlements, especially cities with populations under 500,000, which share about half the region's urban population. Since urban areas account for over 80% of Asia's GDP, research priorities could include detailed estimates of the impact of climate change on various sectors of the urban economy, including the tourism industry (UN-Habitat, 2011). Research on promoting adaptation polices at the municipal level should also be given consideration. It is assumed that the existing policies should be expanded into adaptation; however the implementation of adaptation measures is still in its infancy.

Climate change will not have uniform impact on the population within a country, but rather depends on location, socio-economic conditions and level of preparedness (Begum *et al*., 2011). Negative impacts on agricultural productivity would have significant impacts on the aggregated household welfare, livelihoods and poverty in the region (Zhai and Zhuang, 2009) and this needs to be adequately studied. Low cost options are limited, despite the number of people living below the poverty line in some of the least developed countries such as Bangladesh (Iwasaki *et al*., 2009; Rawlani and Sovacool, 2011). Greater understanding is required on linkages between local livelihoods, ecosystem functions, and land resources for creating a positive impact on local livelihoods and poverty reduction in areas with greater dependency on natural resources (Paul *et al*., 2009). Keeping in view the interconnected nature of the problems across geographical, social and political scales, an emphasis on increased regional collaboration in scientific research and policy making was suggested for reducing climate change impacts on water, biodiversity and livelihoods in the Himalayan region (Xu *et al*., 2009).

While mitigation efforts are essential, the literature suggests that work must begin on building understanding of the impacts of climate change and moving forward with the most cost-effective adaptation measures (Stage, 2010; Mathy and Guivarch, 2010; Cai *et al*., 2008; ADB, 2007). Consequently, for devising mitigation policies, the key information needed are the most cost-effective mitigation measures within sector and across sectors (Mathy and Guivarch, 2010; Cai *et al*., 2008; Nguyen, *et al*., 2007). The costs and benefits of climate change adaptation cannot be analyzed using economic aspects only; other aspects such as climate science, behavioral science, legal and moral aspects also have crucial implications for the outcome of the analysis (Stage, 2010; Agrawala and Fankhauser, 2008; Lecocq and Shalizi, 2007; Begum *et al*., 2006; Metroeconomica, 2004).

24.9. Case Studies

24.9.1. Transboundary Adaptation Planning and Management – Lower Mekong River Basin

The *Lower Mekong River Basin (LMB)* covers an area of approximately 606,000 sq km across the countries of Thailand, Laos, Cambodia and Vietnam (Hinkel and Menniken, 2007). More than 60 million people in the densely populated LMB are heavily reliant on natural resources, in particular agriculture and fisheries for their well-being (MRC, 2009; UNEP, 2010). As two of the five top rice exporting countries globally, Thailand and Vietnam produced 51% of the world's rice exports in 2008. The majority of rice production in these countries is located in the LMB (Mainuddin *et al*., 2011a). About two-thirds of the Mekong Basin's population is involved in fishing to sustain their livelihoods; fishing is particularly important for rural households (Hortle, 2009; Mainuddin et al., 2011b).

Although there is no precise data on the economic value of the LMB fisheries, the total value of inland fisheries in the entire Mekong River Basin (lower and upper) is US$3.9 – 7.0 bn per year, with the export of fish from the four LMB countries reaching about US$5.6 billion in 2008 (FAO, 2008; Mainuddin *et al*., 2011b; MRC, 2010a).

[INSERT FIGURE 24-3 HERE
Figure 24-3: Map of Lower Mekong Basin from Mekong River Commission Technical Paper No. 24, 2009 (MRC, 2009).]

Across the LMB countries observations of climate change over the past 30-50 years include (MRC, 2010b): an increase in temperature (for all riparian countries), rainfall increases in the wet season and decreases in the dry season (e.g. Thailand and Vietnam), intensified flood and drought events (e.g. Laos), and sea level rise (Vietnam's Mekong Delta). Agricultural output has been noticeably impacted by climate-related events. For example in Cambodia from 1996 to 2001, 70% of rice production loss occurred due to flooding and 20% due to droughts (MRC, 2009). In Laos, the areas of rain-fed rice fields destroyed by flooding were 55,172 ha per year on average between 1995 and 2005, accounting for 7% of the country's total cropland (MRC, 2009).Vietnam and Cambodia have been ranked as the countries most vulnerable to the impacts of climate change on their fisheries (Halls, 2009; Allison et al, 2009).

National level climate change adaptation plans have been formulated in all four riparian countries, but a commonly shared scientific forecast on possible future climate impacts as well as an integrated and coordinated adaptation program across the LMB does not exist to date. A range of individual studies that assess future LMB climate differ in the use of underlying climate models and emission scenarios. The existing studies however broadly share a set of expected *future climate changes* in the Mekong Basin (MRC, 2009): increases in temperature, wet season rainfall, and flooding frequency and duration along the Mekong River; decreases in dry season rainfall; sea level rise and salinity intrusion in the Mekong delta.

While significant uncertainties about both the magnitude and location-specific impacts of climate change in the LMB remain, it is expected that *vulnerabilities* will be exacerbated in three areas:

1) Changes in the spatial distribution of agricultural output rates and an overall reduction in food security (MRC, 2009; MRC, 2010b)
2) Loss of fertile land and population displacement in the Mekong river delta (MRC, 2009; MRC, 2010b)
3) Reduced fish survival, growth and reproductive success (UNEP, 2010)

A series of hydropower dams along the Mekong River and tributaries will change the hydrology in the LMB. Climate change, together with impacts from infrastructure development and land-use changes, will exacerbate these changes, likely resulting in disruption to fisheries, with a potential loss in both species diversity and production (Grumbine *et al*., 2012; Ziv *et al*., 2012; Wyatt and Baird, 2007).

To address the climate change related vulnerabilities, adaptation needs primarily arise in areas of improving water management, farming and fishing practices, as well as coastal protection (Johnson et al., 2010; Hoanh et al., 2003; Neo, 2012a). Transboundary initiatives to address climate change are driven by multiple actors, including the Mekong River Commission (MRC), the United Nations Development Program (UNDP) and the Asia Development Bank's Greater Mekong Sub-region programme (ADB GMS) among others (MRC, 2009; Lian and Bhullar, 2011). Despite these initiatives, strong inter-governmental policy development and planning coordination between ministries and different levels of government are largely absent, which has adversely affected the development and implementation of appropriate large scale adaptation strategies (Lian and Bhullar, 2011).

Key challenges and barriers for effective future transboundary adaptation planning and management include*:*

- Lack of a commonly shared scientific forecast on possible future climate impacts across LMB countries as the basis for transboundary adaptation planning (MRC, 2009)
- Sub-optimal coordination among adaptation stakeholders and sharing of best practices across countries (MRC, 2009)
- Insufficient mainstreaming of climate change adaptation into the broader policy frameworks of the national governments in all the four LMB countries (MRC, 2009; Lian and Bhullar, 2011)

- Insufficient integration of transboundary policy recommendations into national climate change plans and policies (Kranz *et al*., 2010)

A stock-take study on the state-of-adaptation practice in the LMB was concluded recently (Ding, 2012; Neo, 2012b; Schaffer and Ding, 2012), showing that only 11% (= 45) projects out of a total of 417 climate change related projects were truly adaptation efforts. Of these 45 projects around 60% are targeting agriculture sectors and rural communities. The stock-take exercise found that no programmatic adaptation approaches were in place, but adaptation practice rather occurred on a project-by-project basis, with single country projects accounting for 89% of all adaptation projects in the LMB. The portfolios of these 45 adaptation projects are characterized by a broad range of actors that do not operate under a coordinated framework. Projects are rather reactive in nature, being developed in response to extreme local weather events or observed water shortages and lack elements of forward-looking strategic and anticipatory planning of expected future climate changes. The private sector is not involved in any adaptation project. Overall adaptation funding and capacity levels to scale up adaptation are limited.

The above study also developed a framework to identify 'successful' climate change adaptation projects in the LMB. Applying this framework to the identified 45 projects, 5 were characterized as successful and documented via case studies (Panyakul, 2012; Khim, 2012; Roth and Grunbuhel, 2012; Mondal, 2012; Brown, 2012). These case studies address issues of building coping capacity for farmers (Panyakul, 2012) or building multi-scale adaptation capacity (Roth and Grunbuhel, 2012) among others.

Common features of these 'successful' projects are:

- Local stakeholder knowledge together with analytical baseline assessments form the basis of robust initial gap assessments and input to the adaptation project planning.
- Multiple local stakeholders, especially local communities, are actively engaged throughout the course of the project.
- The participatory process in each stage of the project develops ownership at the local level and facilitates adoption of good adaptation practices.

Recognizing the state of adaptation practice, funding and capacity development challenges, similarities of climate risk across the LMB countries, diversity of funding and implementing actors and national sovereignty needs, Schaffer and Ding (2012) propose a multi-stakeholder Regional Climate Change Adaptation Action Network approach to enhance the effectiveness and efficiency of future climate change action. This proposed approach follows the theory and successful examples of the Global Action Networks (GANs) (Waddell, 2005; Waddell and Khagram, 2007; WCD, 2000; GAVI, 2011) with the intent of scaling up and improving mainstreaming of adaptation in the LMB.

24.9.2. Tropical Peatlands in Southeast Asia

Tropical peatlands develop only in flat lowland regions with year-round rainfall and are most extensive in Southeast Asia, particularly on the islands of Sumatra, Borneo, and New Guinea (Posa *et al*., 2011). The largest areas are on coastal plains and river deltas, but peatlands can also develop inland on flat or gently convex areas between rivers. They eventually form dome-shaped structures less than 20 m deep that are above the local water table and fed only by rainwater. The modern peatlands of Southeast Asia are relatively young ecosystems, having started growth between the Late Glacial and Mid-Holocene, and peat accumulation appears to have ceased during the late Holocene in Central Kalimantan, possibly as a result of enhanced El Niño activity (Dommain *et al*., 2011). In recent times these peatlands covered around 250,000 km^2 and contained more than 65 Gt of carbon, with two-thirds of this in Indonesia (Page *et al*., 2011). Although traditionally viewed as species-poor, peat swamp forests provide an important habitat for much of the region's fauna, including orangutans and a high diversity of specialized freshwater fish (Posa *et al*., 2011).

Southeast Asian peatland ecosystems were largely intact in 1970 but have been massively impacted over the last 20 years, as a result of logging and conversion to oil palm and pulpwood (Acacia spp.) plantations (Murdiyarso *et al*., 2010). Between 1990 and 2010, forest cover on the peatlands of Peninsular Malaysia, Sumatra and Borneo fell from

77% to 36%, to be replaced by industrial plantations of unknown sustainability and degraded areas covered in ferns, grasses and shrubs (Miettinen *et al*., 2011a). Draining the peat leads to shrinkage and microbial decomposition, and makes the peat itself highly flammable, so the degraded peatlands have become globally significant carbon sources, particular during ENSO-associated droughts (Miettinen *et al*., 2011b; Page *et al*., 2011). Pressures for peatland conversion continue despite these concerns. Tropical peatlands will be very vulnerable to any reduction in rainfall and/or increase in rainfall seasonality over the coming decades, since dry periods lead to lower water tables, enhanced peat decomposition, and greater susceptibility to fire (Page *et al*., 2011). On the other hand, the exceptionally high carbon content makes tropical peatlands a very attractive target for greenhouse gas mitigation projects involving the restoration of groundwater levels (Jaenicke, 2011).

24.9.3. Glaciers of Central Asia and Siberia

The Altai, Pamir, and Tien Shan glaciers represent significant part of the Asian alpine cryosphere supplying up to 40% of water to the Aral, Balkhash and IssikKul Lakes, and Ob and Tarim rivers (Aizen *et al*., 1995; 1998; Surazakov *et al*., 2007). All rivers, except the Ob R. discharge water to central Asian arid endorheic basins populated with over 150 million people from Turkmenistan, Afghanistan, Uzbekistan, Tajikistan, Kyrgyzstan, Kazakhstan, Mongolia and Xinjiang and other north-western provinces of China, and Russia. The rate of glacier area change varies (see Table 24-9). In the last 50 years (1960-2009), central Asian glaciers lost on average 10% of their area and 15% of their ice volume [WG1 AR5 Ch. 4 Section 4.3]. The estimation was based on two sources of remote sensing data over Altai-Sayan, Tien Shan and Pamir: Corona KH Mapping Program (1968-1975), Landsat ETM+ and ASTER images (1999-2003) plus ALOS PRISM 2009. The Altai-Sayan glaciers were evaluated since 1960 using aerial photos, the Tien Shan and Pamir glaciers were computed from 1973-1975 (Aizen, 2011). The accuracy of the changes in glacier area was derived from an independent study of the Akshiirak massif in Tien Shan (Aizen *et al*., 2007). The comparison revealed a 0.7% error in total area, this error was due to differences in manual glacier digitizing and the spatial resolution of the images used in the two studies. Error in total volume of glacier loss is 0.21% (Aizen *et al*., 2006). For the period from 1973 to 2003 glacier ice melt increases total river runoff in heavy glacierized basins by 8% compared to the period from 1942 to 1972 (Aizen *et al*., 2007; Aizen, 2011). The studies on regional (Aizen *et al*., 1997; 2010) and local (Finaev, 2004) climate change in Central Asia revealed a positive trend in annual/warm season air temperatures with more significant rate of air temperature growth at low elevations. According to Giese et al., (2007) warming was not steady, there were three main thrusts: 30^{th}, 50^{th} and 70^{th}. Investigations on precipitation changes revealed negative trend over the SE Mongolia (Yatagai and Yasunari 1994), Northern China (Xu 2001) and inner /central Tien Shan (Aizen *et al*., 1997). Aizen *et al*. (2010), Finaev (2004) analyses declared that the average annual precipitation did not change significantly throughout central Asia, increasing only 0.9%. Areas with surplus precipitation were larger than areas with precipitation deficit, while the absolute values of positive differences were lower than the negative absolute values. Surplus precipitation occurred in winter and at low altitudes, in regions surrounding the Tien Shan mountains.

The glaciers of the Altai-Sayan mountains are located in the most northern periphery of the Central Asia mountain system at a south edge of the Arctic basin in Siberia (see Figure 24-4). Altai-Sayan glaciers lost on average 14% area from 1960s to 2009 (Surazakov *et al*., 2007; Shahgedanova *et al*., 2010; Aizen, 2011). The accelerated glacier melt and glacier area reduction in the Altai-Sayan was caused mainly by an increase of summer air temperatures by 1.03ºC for the last 50 years (Savelieva et al, 2000; Aizen et al., 2010). The elevation of glaciers in the Pamir mountains reaches 7,700 m a.s.l. (Muztagata-Kongur glacierized massifs). Pamir glaciers nourish the Amu Dariya River, the major Aral Sea water stream. During the last 50 years (1960-2009), the largest glacier area losses (up to 12-15%) have been observed in the western and south-western Pamir and the smallest in central and eastern Pamir (3- 5%) (Khromova *et al*., 2006; Aizen *et al*., 2010: 2011). The Fedchenko Glacier in central Pamir, which is the world's largest alpine glacier outside of the Polar regions (Kotlyakov, 1997; Aizen, 2011; Lambrecht *et al*., 2013) (72 km long, 714 km^2 area, and 900 m max ice thickness) retreated 755 m between 1958 and 2009, losing only 2 km^2. The Tien Shan glaciers are located in the largest mountain system in central Asia, stretching 2000 km from west to east. The Tien Shan glaciers are the major sources of water for Balkhash and IssikKul lakes, and the Sir Darya and Tarim rivers. Summer precipitation decreased by 10% and the Tien Shan glaciers lost 8.5% of their total area on average during the last 50 years. The largest glacier area lost is observed in the northern and western Tien Shan (14.3%) due to a decrease in annual precipitation (-20mm) at elevations above 3,000 m a.s.l. and increased air

temperatures by 0.44°C. Smaller glacier recessions have been observed in the inner and central Tien Shan (10% and 5% respectively). In central Tien Shan glacier recession is minimal due to high-elevated accumulation areas (up to 7,000 m a.s.l.). Thus, the central Tien Shan and central Pamir glaciers have been revealed as more stable glaciers to climate changes in central Asia (Aizen, 2011; Bamber, 2012; Jacob *et al*., 2012; Lambrecht *et al*., 2013). The eastern Tien Shan lost 12% of the total glacier area. On average, air temperatures increased by 0.8°C and precipitation decrease by 7% at the equilibrium line altitude (ELA) between the 1960s and 2009 in Tien Shan (Aizen, 2011).

[INSERT TABLE 24-9 HERE
Table 24-9: Recent publications on central Asia glaciers changes.]

[INSERT FIGURE 24-4 HERE
Figure 24-4: The difference in losses of glacier area in Altai-Sayan, Pamir and Tien Shan. Remote sensing data analysis from 1960s (Corona) through 2009 (Landsat, ASTER and Alos Prism).]

Simulation models forecast that significant glacier degradation will begin when (ELA) has increased by 600 m compared to the end of the 20th century (Aizen *et al.,* 2007). Then, the area covered by central Asian glaciers may shrink by 40% and the glacier volume by 60% of the current state. The IPCC WGI TAR in five AOGCMs under a range of forcing scenarios for 2100 compared to 1961 to 1990 predict, on average, an increase in regional air temperature of 2ºC to 8ºC (about 4ºC) and an increase in magnitude of precipitation of 0.8-1.2 (about 1.1 times) (Giorgi *et al*., 2001). If the air temperature increases to the greatest predicted value, i.e. by 8ºC, and precipitation increases to its maximum predicted value, i.e. by 1.24 times the current rate, then the model predicts a 970 m increase in ELA and the number of Tien Shan glaciers, glacier covered areas, and glacier volume are predicted to shrink correspondingly by 94%, 69%, and 75% of the current state. However, under the threshold predicted conditions, if air temperature increases by 8ºC and precipitation decreases to the minimum predicted value, i.e. by 0.84 times the current rate, then current glaciations will disappear. If air temperature increases to the minimum predicted value, i.e. by 2ºC, and if precipitation increases to the maximum predicted value 1.24 times the current value, then the simulation model predicts almost no changes in the number of glaciers, glacier covered area (GCA), and glacier volume, while glacier runoff will increase by 1.25 times of the current value (Aizen *et al.,* 2007).

Further changes in glacier water resources availability will bring the CA closer to a tipping point of an irreversible ecological and socio-economical collapse, significantly contribute to progressive droughts and land degradation. Inflowing water discharges only through seepage or evaporation without glacier/snow transition, eventually develop saline water, many lakes will contract and the ecosystems will disrupt. In basins with small glacierized areas, the disappearance of small glaciers has already led to a decline in river discharge, strongly affecting downstream agriculture and settlements of the densely populated arid region [24.4.1].

The Altai and inner Tien Shan glaciers did not exist in the Bølling-Allerød (BP) and regenerated during the Young Dryas episode. Central Asian glaciers survived the warmest periods during the last 12,500 years, i.e., Holocene Thermal Maximum (circa 7,600BP), Medieval Climate Optimum, when mean air temperature was about 4.2ºC higher than modern, i.e. the annual average temperature in the last three decades. Since that, the mean air temperature should be at least 5ºC higher than modern (Aizen *et al*., 2013) to complete modern glacier disappearance (Aizen *et al.,* 2010).

24.9.4. Is the Aral Sea Dying?

The Aral Sea (see Figure 24-5) was a very large lake in Central Asia that was the fourth largest in area in the world before the 1960s (Letolle, 2008; Kostianoy and Kosarev, 2010). It is located in the Karakum and Kyzylkum deserts. Navigation and the fisheries (yearly catches of 44,000 tons) were developed there. The deltas of two major rivers of Central Asia, the Amudarya and the Syrdarya, that bring waters to the Aral Sea, were known for their fisheries, biodiversity, reed production, and muskrat rearing. The local population used to work in water infrastructure related spheres (Nihoul *et al.,* 2002; Zonn *et al.,* 2009).

[INSERT FIGURE 24-5 HERE
Figure 24-5: The satellite view of the Aral Sea acquired on 7 September 2012 from MODIS-Aqua. Image courtesy by A.G. Kostianoy (P.P. Shirshov Institute of Oceanology, Moscow, Russia) and D.M. Solovyov (Marine Hydrophysical Institute, Sevastopol, the Ukraine), based on the LAADS Web, NASA-Goddard Space Flight Center data (http://ladsweb.nascom.nasa.gov/). The red line indicates the Aral Sea coastline back in 1960. The yellow line indicates the border between Kazakhstan and Uzbekistan.]

Since 1960, the water resources of the Amudarya and Syrdarya rivers have been excessively used in order to increase irrigation of agricultural lands as well as to create artificial water reservoirs, which later proved to be irrational (Glantz, 1999; Kostianoy and Kosarev, 2010). Hence the water balance of the Aral Sea was disrupted, and irreversible changes in the regime of the sea occurred which later led to one of the "largest ecological disasters of the twentieth century" (Letolle and Mainguet, 1993; Micklin and Williams, 1996; Glantz, 1999). For the last fifty years a progressive desiccation of the Aral Sea and deterioration of its environment has been observed. During those years the sea surface shrunk from 66,100 km^2 (1961) to 10,400 km^2 (2008); the sea volume decreased to 110 km^3 from 1,066 km^3 (1961); the sea level fell by 24 m (in 1961 the maximum depth was 69 m); and its salinity (mineralization) increased from 10 to 116 p.p.t. in the western part and to 210 p.p.t. in the eastern part of the Large Aral Sea (Kostianoy and Wiseman, 2004; Zavialov, 2005; Kostianoy and Kosarev, 2010).

The ongoing Aral Sea desiccation and salinization have resulted in critical changes in its shape, physical and chemical state, and biodiversity. Related economic activities lost their importance. The consequences of the sea degradation represent a big threat to the quickly growing population in the Priaralie (from 14 m people in 1960 to 45 m in 2006) due to such factors as water quality loss, lack of fresh water, dust and salt storms, salinization of soils, various diseases, and regional climate change (Kostianoy and Kosarev, 2010).

Irrational use of waters of Amudarya and Syrdarya is not the only reason for the Aral Sea desiccation. Regional climate change (decrease in precipitation and increase in air temperature) also seems to play a significant role in this process. Assessments of the water amount precipitated over the Amudarya catchment area for the period between 1979 and 2001 showed a critical decrease from about 7.5 to 4.5 km^3 per month on average (Nezlin *et al.,* 2004). According to estimates of the IPCC AR4, the rise in the mean annual air temperature in the Aral region in 1960–2000 was 1^0C (IPCC, 2007; Lioubimtseva and Henebry, 2009). Thus, regional climate change significantly influenced the water balance of the Aral Sea in the past 30 years, leading to its "supplementary" desiccation in addition to irrational water use.

By 2012, the main progress in saving the Aral Sea was achieved only in the Kazakh part, with the Kokaral dam construction between the eastern part of the Large Aral Sea and the Small Aral Sea in August 2005 (Kostianoy and Kosarev, 2010). Today, the Small Aral Sea is slowly reviving and small fishery production is growing, while the Large Aral Sea keeps on disappearing. Since 2010, the former eastern part of the Large Aral Sea has been a wetland which is periodically filled with snowmelt and rain water and partly desiccated in the dry seasons. The western part of the Large Aral Sea, being a relatively narrow and deep lake, may slowly die in the absence of an external water supply (Kostianoy and Kosarev, 2010; Micklin, 2010; Breckle *et al.,* 2012; Kostianoy, 2012).

Frequently Asked Questions

FAQ 24.1: What will be the projected impact of climate change on freshwater resources in Asia by the 2050s?
Asia is a huge and diverse region, so both climate change and the impact on freshwater resources will vary greatly across it. Adequate water resources are particularly important for Asia because of the heavy dependence of the agricultural sector on precipitation, river runoff and groundwater. There is low confidence in the future climate projections of precipitation on a regional scale and thus in predictions of climate change impacts on water resources availability. However, water scarcity is expected to be a big challenge in many Asian regions because of increasing water demand from population growth and higher standards of living. Shrinkage of glaciers in central Asia is expected to increase due to climate warming, which will influence downstream river runoff in these regions. Better water management strategies are needed to ease water scarcity. Water saving technologies and changing to more drought tolerant crops have been found to be successful adaptation options in the region.

FAQ 24.2: How will climate change affect biodiversity and ecosystems in Asia?

Rising temperatures are already leading to changes in the timing of life-history events, including leafing, flowering and leaf fall in plants, and migration and breeding in animals, and these changes are expected to continue. Changes in temperature and, less predictably, rainfall will also lead to changes in the distributions of plants and animals, most dramatically in Northern Asia, where boreal forest and shrubs will expand into tundra, and evergreen conifers will invade deciduous larch forest. On mountains, species will move upslope. In much of Asia, however, fragmentation of natural ecosystems will limit the ability of species to track changes in climate, increasing the risk of extinctions. Impacts on inland waters will interact with a wide range of other human impacts, including dam construction and pollution, but are expected to have an overall negative impact on the biota. Negative impacts on coastal and marine biodiversity are likely in the tropics, with coral reefs particularly vulnerable to both warming and ocean acidification, and also for ice-dependent species in the Arctic.

FAQ 24.3: How is climate change affecting permafrost in Asia?

Permafrost (permanently frozen ground) has degraded in recent decades in Siberia, Mongolia, China and Central Asia, and it is projected that permafrost degradation during the 21st century will spread from the southern and low-altitude margins, advancing northwards and upwards. In the Asian Arctic, changes in permafrost and in storm wave energy, as a result of sea-level rise and retreating sea ice, make coasts more vulnerable to erosion. It is projected that rates of coastal erosion in Asian Arctic will increase during the 21st century.

FAQ 24.4: How will climate change affect food production and food security in Asia?

Climate change impacts on crop production will be generally negative for most crops in Asia. For rice, most simulation models show that higher temperatures will lead to lower rice yields as a result of a shorter growing period. However, some studies indicate that the CO_2 fertilization effect could lead to rice yield increases despite climate change. This uncertainty on the overall effects of climate change and CO_2 fertilization is also generally true for other crops such as wheat, sorghum, barley, and maize among others. The impacts of climate change specifically changes in temperature and precipitation regimes on food production and food security will vary within regions and countries, increasing yields for some areas (e.g. cereal production in north and east Kazakhstan) and decreasing yields for others (e.g. wheat in the Indo-Gangetic Plain of South Asia). There are many potential adaptation strategies, such as crop breeding, changing crop varieties, adjusting planting time, water management, diversification of crops and a host of indigenous practices.

FAQ 24.5: How will climate change affect human health in different parts of Asia?

More frequent and intense heatwaves will increase mortality and morbidity in vulnerable groups in urban areas. The transmission of infectious disease will be affected due to changes in air and water temperatures (such as cholera epidemics in coastal Bangladesh, and schistosomiasis in inland lakes in China) and altered rain patterns and water flows (e.g., affecting diarrheal outbreaks in rural children). Changes in the geographical distribution of vector-borne diseases will be most noted close to their distribution limits. Outbreaks of the vaccine-preventable Japanese encephalitis in the Himalayan region and malaria in India and Nepal have been linked to rainfall.

FAQ 24.6: Who are the people most at risk in Asia from climate change?

People living in low lying coastal zones and flood plains are probably most at risk from climate extremes in Asia, with vulnerability increased by rising sea-levels. Such areas are home to 50% of Asia's urban population. Asia has more than 90% of the global population exposed to tropical cyclones. Settlements on unstable slopes or landslide prone areas face increased likelihood of rainfall induced landslides. Rural poverty in parts of Asia could be exacerbated due to negative climate change impacts on the rice crop and increase in food price and cost of living. Urban population growth will lead to urban land-use and land-cover changes and in turn will have impacts on climate.

FAQ 24.7: What are the challenges in research on climate impacts, vulnerabilities and adaptation in Asia?

Because of its size and diversity, gaps in data are a bigger challenge for Asia than in other parts of the world. For example, trends in precipitation are less available than data on trends in temperature, data on observed climate change and changes in extreme climate events does not cover most Asian regions. For freshwater resources, new models of future rainfall changes, developing of water managing strategies and study on water saving technologies

are needed. Biodiversity data and data on biome boundaries shift are incomplete, and long-term monitoring, especially in protected areas is needed to fill these gaps. Studies on agricultural sector and appropriate adaptation options, on social-economic and institutional dimension, on urban settlements and industry should also be given priority. A particular challenge is to assess how the comprehensive economic, social and cultural transformation processes happening in most parts of Asia will influence future dynamics in vulnerability patterns and adaptive capacity of different countries, economic sectors and social groups.

Cross-Chapter Box

Box CC-TC. Case Study Building Long Term Resilience from Tropical Cyclone Disasters

[Yoshiki Saito (Japan), Kathleen McInnes (Australia)]

Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves and storm surge, all of which can have major impacts on society and ecosystems. For example, Bangladesh and India account for 86% of mortality from tropical cyclones (Murray *et al*., 2012), which is mainly due to the rarest and most severe storm categories (i.e. Categories 3, 4, and 5).

About 90 tropical cyclones occur globally each year (Seneviratne et al, 2012) although interannual variability is large. Changes in observing techniques particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities. Therefore, SREX concluded that there is *low confidence* that any observed long-term (i.e. 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne, *et al.,* 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is *likely* to increase. Regionally specific projections have *lower confidencelower confidence* (see WG1 Box 14.2).

Longer term impacts from tropical cyclones includes salinisation of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer term changes associated with climate change.

Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density in expanding urban areas (Nicholls *et al*., 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray *et al*., 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga *et al*., 2003; Brakenridge *et al*., 2012). The flooded areas were captured by a NASA MODIS image on 5 May 2008 (Figure TC-1).

[INSERT FIGURE TC-1 HERE
Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al*., 2012).]

Murray *et al*. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargs in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation (Murray et al, 2012). Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3,400 compared to over 138000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multi-storied cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and

coastal reforestation of mangroves. Birkmann and Teichman, (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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Table 24-1: The 51 countries/regions in the six sub-regions of Asia.

Sub-region	Countries/Regions	
Central Asia (5)	• Kazakhstan • Kyrgyzstan • Tajikistan	• Turkmenistan • Uzbekistan
East Asia (7)	• China, Hong Kong Special Administrative Region (Hong Kong) • China, Macao Special Administrative Region • Japan	• North Korea • People's Republic of China (China) • South Korea • Taiwan Province of China (Taiwan)
North Asia (2)	• Mongolia	• Russia (East of Urals)
South Asia (8)	• Afghanistan • Bangladesh • Bhutan • India	• Maldives • Nepal • Pakistan • Sri Lanka
Southeast Asia (12)	• Brunei • Indonesia • Lao People's Democratic • Malaysia • Myanmar • Papua New Guinea	• The Philippines • Republic Cambodia • Singapore • Thailand • Timor-Leste • Vietnam
West Asia (17)	• Armenia • Azerbaijan • Bahrain • Georgia • Iran • Iraq • Israel • Jordan	• Kuwait • Lebanon • Occupied Palestinian Territory • Oman • Qatar • Saudi Arabia • Syria • United Arab Emirates • Yemen

Table 24-2: Summary of key observed past and present annual mean temperature trends in Asian countries/regions.

Sub-region	Countries/Regions	Unit	Change (Period)	Reference
Central Asia	Kazakhstan	°C/10y	+0.31 (1936-2005)	Kryukova *et al*., 2009
	Kyrgyzstan	°C	+1.6 (1901-2000)	Iliasov *et al*., 2003
	Tajikistan	°C/10y	+0.1 to +0.2 (1940-2005)	Karimov *et al*., 2008
East Asia	Hong Kong	°C/10y	+0.12 (1885-2008), +0.16 (1947-2008), +0.27 (1979-2008)	Ginn *et al*., 2009
	Japan	°C/100y	+1.15 (1898-2010)	JMA, 2011
	China	°C/10y	0.09±0.017 (1900-2006), 0.26±0.032 (1954-2006), 0.45±0.13 (1979-2006)	Li *et al*., 2010
		°C/10y	+0.03 to +0.120 (1906-2005), +0.03 to +0.120 (1908-2007)	Ren *et al*., 2012
	South Korea	°C	+1.87 (1908-2008), +1.37 (1954-2008), +1.44 (1969-2008)	Kim *et al*., 2010
	Taiwan	°C/10y	+0.14 (1911-2009), +0.19 (1959-2009), +0.29 (1979-2009)	Hsu *et al*., 2011
North Asia	Mongolia	°C	+2.14 (1940-2005)	Dagvadorj *et al*., 2009
	Russia	°C	+1.29 (1907-2006), +1.33 (1976-2006)	Anisimov *et al*., 2008
South Asia	Afghanistan	°C	+0.6 (1960-2008)	Savage *et al.*, 2009
		°C/10y	+0.13 (1960-2008)	
	Bangladesh	°C/10y	+0.097 (1958-2007)	Shahid, 2010
	India	°C	+0.56 (1901-2009)	Attri and Tyagi, 2010
		°C/100y	+0.68 (1880-2000)	Lal, 2003
		°C/y	+0.0056 (1948-2008)	Ganguly, 2011
	Nepal	°C/y	+0.06 (1977-1994)	Shrestha *et al.*, 1999
	Pakistan	°C	+0.57 (1901-2000), +0.47±0.21 (1960-2007)	Chaudhry *et al.*, 2009
		°C/10y	+0.099 (1960-2007)	
	Sri Lanka	°C/y	+0.005 to +0.035 (1961-2000)	Iqbal, 2010
		°C/10y	+0.3 to +0.93 (1869-2007), +0.75 to +0.94 (1910-2007)	de Costa, 2008
Southeast Asia	The Philippines	°C	+0.648 (1951-2010)	PAGASA, 2011
		°C/y	+0.0108 (1951-2010)	
West Asia	Armenia	°C	+0.85 (1935-2007)	Gabrielyan *et al*., 2010
Tibetan Plateau		°C(°C/10y)	+1.8 (0.36/10y) (1961-2007)	Wang *et al*., 2008
		°C/10y	+0.447 (1962-2001)	Xu *et al*., 2008

Table 24-3: Summary of key observed past and present annual mean precipitation trends in Asian countries/regions.

Sub-region	Countries/Regions	Unit	Change (Period)	Reference
Central Asia	Kazakhstan	No definite national trend. (1936-2005)		Kryukova *et al.*, 2009
	Kyrgyzstan	mm	+23 (+6%) (1901-2000)	Iliasov *et al.*, 2003
	Tajikistan *plain region	%	+8 (insignificant) (1940-2005)	Karimov *et al.*, 2008
	*mountainos region	%	-3 (insignificant) (1940-2005)	Karimov *et al.*, 2008
	Turkmenistan	mm/10y	+12 (1931-95)	MNPT, 2000
East Asia	Hong Kong	mm/10y	+25 (1885-2008)	Ginn *et al*., 2009
	Japan	No clear trend		MEXT *et al*., 2009
	South Korea	%	+5.6 (2001-2008)	Kim *et al*., 2010
North Asia	Mongolia	mm/y	-0.1 to -2.0 (1940-2005)	Dagvadorj *et al*., 2009
	Russia	mm/10y	+7.2 (1976-2006)	Anisimov *et al*., 2008
South Asia	Afghanistan	mm/m	-0.5 (1960-2008)	Savage *et al*., 2009
		%/10y	-2 (1960-2008)	
	Bangladesh	mm/y	+5.53 (1958-2007)	Shahid, 2010
	India	No significant national trend (1901-2009)		Attri and Tyagi, 2010
	Pakistan	mm	+61 (1901-2007), -156 (1901-54), +35 (1955-2007)	Chaudhry *et al*., 2009
	Sri Lanka	mm/y	-1.55 to -19.06 (1961-2000)	Iqbal, 2010
Southeast Asia	Indonesia *Brontas Catchment	mm/y	-1.23 to -24.25 (1955-2005)	Aldrian and Djamil, 2008
West Asia	Armenia	%	-6 (1935-2007)	Gabrielyan *et al*., 2010
Tibetan Plateau		mm/y	+0.614	Xu *et al.*, 2008

Table 24-4: Summary of projected changes for a variety of climate parameters [WG1 AR5 SOD Ch. 14].

Sub-region	T/P	Projected changes
Central and North [AR5 WGI SOD 14.7.8]	T	Central: Similar warming magnitude in winter and summer. Northern: A stronger warming trend during winter.
	P	Central: Less certain Northern: *Very likely* increase. Central and Northern: *Likely* increase of extremes
East [AR5 WGI SOD 14.7.9]	T	*Very likely* increase by end of 21st C., more in summer than in winter. *Virtually certain* increase significantly over East Asia by end of 21st C., with larger magnitude over northern China and in winter (high confidence).
	P	Decrease mainly in winter, since there is very little precipitation in summer under present-day conditions. *Likely* increase of East Asian summer monsoon intensity throughout 21st C. and of summer precipitation over whole of East Asia (medium confidence) *Likely* increase over Yangtze River Valley, Korean peninsula and Japan during Meiyu-Changma-Baiu season in May-July. *Very likely* increase of extremes over most of southeastern China in all seasons, and over Japan in summer.
West and South [AR5 WGI SOD 14.7.10]	T	West and South: *Virtually certain* increase (high confidence)
	P	West and South: 'Wet gets wetter and dry becomes drier' but with large uncertainties West: *Likely* less precipitation in April to September half year (low to medium confidence) South: *Likely* more precipitation than at present (low to medium confidence)
Southeast [AR5 WGI SOD 14.7.11]	T	*Very likely* continuous warming through 21st C. (high confidence). *Likely* substantial sub-regional differences *Very likely* greater increase at night than during the day for all seasons *Very likely* continuous increase in hot days and warm nights, and decline in cooler weather.
	P	*Likely* averaged increase across the region with strong geographical variations (medium confidence)
T: Temperature, P: Precipitation		

Table 24-5: Summary of key observed past and present climate change impacts in Asia.

Sub-Region	Countries/Regions (Area)	***Parameters:*** Observed changes	Period	References
Central Asia	Kazakhstan (Steppe region in north)	***Normalized Difference Vegetation Index (NDVI):*** Decline (browning)	1982-2008	De Jong *et al.*, 2012
	Kazakhstan (Northern Tien Shan Mountains)	***Permafrost temperature at depths of 14-25 m:*** +0.3 to +0.6°C	1974-2004	Marchenko *et al.*, 2007; Zhao *et al.*, 2010
		Active layer thickness: +23%		
	Uzbekistan (Zerafshan River Basin)	***Water monthly discharge:*** Significant increases in spring and decreases in summer	1923-2006	Olsson *et al.*, 2010
	Kazakhstan, Uzbekistan, Kyrgyzstan (Main lakes)	***Surface area change:*** -49.62% (Aral Sea), -75.7% (Balk hash) , -2.61% (Ebinur), -8.37% (Issyk-Kul) +5.85% (Zaysan), -9.18% (Bosten)	1975-2007	Bai *et al.*, 2012
East Asia	Japan (Upper part of Kurobe Dam, Toyama)	***Runoff:*** Decreased by 40mm, slightly decreased and more in winter and spring, less in summer	1974-2004	Shinohara *et al.*, 2009
	Japan (Multiple sites)	***Spring leafing and flowering:*** Earlier by < 3 days per decade	Last 60 years	Ogawa-Onishi & Berry, 2013
		Changes in species distributions: Northwards by < 126 km per decade	Last 50-70 years	
	Japan (Seas around Japan)	***Changes in species distributions:*** Northwards expansion of fish, corals and algae.	Recent decades	Nagai *et al.*, 2011; Yamano *et al.*, 2011; Tian *et al.*, 2012.
	China (Shiyang River basin)	***Streamflow:*** Five of eight catchments showing significant decreasing trends	1950-2005	Ma *et al.*, 2008
	China (Dongjiang River)	***Runoff:*** Not significant change. Clear increased trend at two of three stations in low-flow period	1956-2000	Liu *et al.*, 2010a
	China (Tarim River Basin)	***Streamflow:*** Three of four river with increasing streamflow except Akesu River	1960-2005	Zhang *et al.*, 2010
		Mainstreams runoff: Decreased by 41.59% (1970s), 63.77% (1980s), 75.15% (1990s)	1957-2003	Hao *et al.*, 2008
		Runoff: In 1990s runoff from headwaters of Aksu and Yarkand River increased by 10.9%	1955-2000	Chen *et al.*, 2007b
	China (Baimashi Basin)	***Runoff:*** Decreased by 1.88% per year, decreasing from 1960s	1950-2000	Wang *et al.*, 2010
	China (Upper reaches of Tarim River Basin)	***Runoff:*** Aksu River showed a significant increasing trend with 10.9%. Three of four rivers showed an increase trend with one showed subtle reduction	1958-2004	Yaning *et al.*, 2009
	China (Laohahe Basin)	***Runoff:*** Runoff in 1980-2008 decreased by 36% compared with 1964-1979	1964-2008	Jiang *et al.*, 2011
	China (Hun-Tai River Basin)	***Streamflow:*** Downward trends	1961-2006	Zhang *et al.*, 2011
	China (Kaidu River Basin)	***Runoff:*** Increasing with rate of 8.4mm/decade; 1994-2009 increased 26.4% compared to 1960-1993	1960-2009	Chen *et al.*, 2012
	China (Haihe River Basin)	***Runoff:*** Significant downward trends	1957-2000	Wang *et al.*, 2012
	China (Pearl River, Yangtze River, Yellow River, Liao River, Songhua River)	***Runoff:*** Increased by 10% (Pearl River), had little change (Yangtze River), decreased by 80% (Yellow River), decreased by 54% (Liao River), decreased by 14% (Songhua River)	1951-2000	Xu, K. H. *et al.*, 2010
	China (Qinghai-Tibetan Plateau)	***Active layer thickness along Qinghai-Tibetan Highway:*** Mean rate of +7.5 cm/year	1995- 2007	Wu & Zhang, 2010
		Position of lower altitudinal limit of permafrost in north: Moved up by 25 m	Last 30 years	Cheng & Wu, 2007; Li *et al.*, 2008
		Position of lower altitudinal limit of permafrost in south: Moved up by 50-80 m	Last 20 years	
		Total area of glaciers of QTP and surrounding areas: Decreased by c. 9%, from 13363 ± 668 km^2 to 1213 ± 607 km^2	1970s-2000s	Yao *et al*., 2012
	China (Whole country)	***Start of plant growth in spring:*** Earlier start by 2.9 days per decade	Last 30 years	Ma and Zhou, 2012
	China	***Rice yield*****:** Positive correlation to temperature.	1981-2005	Zhang *et al*., 2010
	Taiwan (Mountains)	***Plant distributions:*** Upper limits shifted upwards by 3.6 m per year	1906-2006	Jump *et al.*, 2012
North Asia	Mongolia (Kherlen River Basin)	***Underground water storage:*** No evidence for long-term storage change	1947-2006	Brutsaert, W. *et al.*, 2008
	Mongolia (Khentey Mountains)	***Growth of Siberian larch forest in forest-steppe ecotone:*** a. Tree-ring analysis shows a decreasing annual increment. b. Regeneration of larch decreased	1940s -2010	Dulamsuren *et al.*, 2010a; 2010b
	Mongolia (Hovsgol Mountain region)	***Mean annual ground temperature at 10 m depth:*** Increased on average by 0.02-0.03°C/year	Last 10-40 years	Sharkhuu *et al.*, 2008; Zhao *et al.*, 2010
	Mongolia (Hangai and Khentei Mountain regions)	***Mean annual ground temperature at 10 m depth:*** Increased on average by 0.01-0.02°C/year	Last 10-40 years	Sharkhuu *et al.*, 2008; Zhao *et al.*, 2010

	Russia, East of Urals (Siberia)	***Forest-tundra ecotone:*** a. Larch stands crown closure, and larch invasion into tundra at a rate of 3-10 m/year. b. Shrub expansion in arctic tundra as result of an increase in shrub growth.	1970-2000	Kharuk *et al.*, 2006; Myers-Smith *et al*., 2011; Blok *et al*., 2011
		Distribution of dark needle conifers (DNC), Siberian pine, spruce and fir: Invasion of DNC and birch into larch habitat	1980-2010	Kharuk *et al.*, 2010c, d; Osawa *et al.*, 2010; Lloyd *et al.*, 2011
		Permafrost temperature at zero annual amplitude: Warming of permafrost in most permafrost observatories in Asian Russia by 0.5-2°C.	1970s-1990s	Romanovsky *et al.*, 2008, with supplement; Romanovsky *et al.*, 2010
		Permafrost temperature at zero annual amplitude: No significant warming.	2000-2007	
		Permafrost temperature at zero annual amplitude: Warming of permafrost resumed at many locations predominantly near Arctic coasts.	2007-2008	
	Russia, East of Urals (Asian Arctic)	***Average erosion rate of coastline:*** 0.27-0.87 m/year	-	Lantuit *et al.*, 2012
	Russia, East of Urals (Ural Mountains)	***Area of glaciers:*** Decreased by 20-30% in total	1953-1981	Anisimov *et al.*, 2008
	Russia, East of Urals (Kodar Mountains)	***Area of glaciers:*** Exposed ice area (EIA) declined by c. 44%	ca. 1963-2010	Stokes *et al*., 2013
		Area of glaciers: EIA declined by c. 40%, from 11.72 ± 0.72 km^2 to 7.01 ± 0.23 km^2	1995-2010	
	Russia, East of Urals (Suntar Khayata Range)	***Area of glaciers:*** Decreased by19.3%	Mid. 20th C.-2003	Ananicheva *et al*., 2005, 2006
	Russia, East of Urals (Chersky Range)	***Area of glaciers:*** Decreased by 28 %	1970-2003	Anisimov *et al*., 2008
	Russia, East of Urals (Kamchatka)	***Area of glaciers:*** Decreased for some glaciers, increased for others	Since Mid 19th C.	Anisimov *et al*., 2008
South Asia	India (Upper Indus Basin)	***Water stress:*** No strong evidence for marked reduction in water resources	1961-2004	Archer *et al*., 2010
	India (Headwater of Kosi River)	***Water resources:*** Reducion in groundwater recharge, 36% of springs have dried, heads of perennial streams have dried and water discharge in springs and streams have decreased considerably	1990-2010	Tiwari & Joshi, 2012
	India (Andaman Islands)	***Coral health:*** Mass bleaching	2010	Krishnan *et al.*, 2011
	Nepal (Himalayan region)	***Water resources:*** Significantly moving snowline		Karki *et al.* 2009;
	Nepal (Shorong, Khumbu, Langtang, Dhaulagiri, Kanchenjunga)	***River discharge:*** Decreasing trend in Karnali and Sapta Koshi; increasing trend in Narayani. No trend in southern rivers.	1970s-2000s	Shrestha & Aryal 2011
	Pakistan, India, Nepal, Bhutan (Himalayas)	***Start of plant growth in spring:*** Earlier start by 1.9 days per decade	1982-2006	Shrestha *et al.*, 2012
		Livelihoods: Leave farming due to repeated droughts	-	Kulkarni & Rao, 2008
Southeast Asia	Republic Cambodia	***Poverty:*** Loss of crops, income and fallows	-	Kulkarni & Rao, 2008
	Indonesia (Province of Papua)	***Area of mountain glaciers Puncak Jaya, Central Cordillera, New Guinea Island:*** Reduced from 19.3 km^2 to 7.3 km^2 (Mid 19th C.-1972), Reduced from 7.3 km^2 to 2.1 km^2 (1972-2002)	Mid 19th C. - 2002	Prentice & Glidden, 2010; Allison, 2011
	Malaysia (Mt Kinabalu, Sabah)	***Altitudinal distributions of moth species:*** Uphill shifts by average 83 m (upper) and 86 m (lower)	1965-2007	Chen *et al.*, 2011
	Indonesia, Malaysia, Singapore	***Coral health:*** Mass bleaching and subsequent mortality	2010	Guest *et al*., 2012
West Asia	Jordan	***Wheat and barley yield*****:** In 1999, total production and average yield for wheat and barley were lowest among years due low rainfall which was 30% of average.	1996-2006	Al-Bakri *et al*., 2010
	Azerbaijan, Georgia (Southern macroslope of Greater Caucasus Range)	***Area of glaciers:*** Decreased by 31.2% in total	1895-2000	Anisimov *et al*., 2008
	Iran, Iraq, Kuwait, Qatar, Saudi Arabia, UAE	***Coral health:*** Mass bleaching and subsequent mortality	1996-2012	Coles & Riegl, 2013
Kazakhstan, Kyrgyzstan, Tajikistan, China, Mongolia, Russia (East of Urals), Afghanistan (Altai-Sayan, Pamir, and Tien Shan Mountains)		***Area of glaciers:*** Decreased on average by 10%, accuracy of area loss estimate: 0.7%	1960-2009	Aizen, 2011; Aizen *et al.*, 2006, 2007
		Ice volume of glaciers: Decreased on average by15%, accuracy of volume loss estimate: 0.21%		
East and South Asia		***Poverty:*** Disproportionately impacts by climate related hazards	-	Kim, 2011
East and Southeast Asia (Mekong region)		***Livelihoods:*** Increased migration due to environmental (e.g. rapid onset disasters), social and economic reasons	-	Warner, 2010; Black *et al.*, 2011

Table 24-6: Summary of key future climate change impacts in Asia.

Sub-Region	Countries/Regions (Area)	***Parameters*: Projected impacts**	Scenario/GCM (RCM)/Period (Base year)	Reference
Central Asia	N. & E. Kazakhstan	***Crop yield (cereal):*** Benefit from longer growing season, warmer winters and slight increase in winter precipitation		Lioubimtseva & Henebry, 2009
	W. Turkmenistan & Uzbekistan	***Crop yield (cotton):*** Negative impacts by frequent droughts		
East Asia	Japan (Tohoku and Hokuriku)	***River discharge:*** 200% higher in Feb., 50-60% lower in May.	A1B/AGCM/2080-2099 (1980-99)	Sato, Y. *et al*., 2012
	Japan	***Rice transplanting date:*** Northward shift of isochrones of safe transplanting dates for rice seedlings.	A2/MRI-CGCM2 (RCM20) /2081-2100 (1971–2000)	Ohta & Kimura, 2007
	China (Tarim River Basin)	***Flow:*** Positive change 1.3-12.8% in BYBLK and 17.7-29.7% in DSK	A2, A1B, B1/18GCMs/2046-65 (1979-98)	Liu *et al*., 2011
	China (Poyang Lake)	***Annual catchment inflow:*** Increased by 2.9% (A1B) and 6.5% (B1), decreased by 5.2% (A2).	A1B, B1, A2/ ECHAM5/ 2011-50 (1961-2000)	Ye *et al*., 2011
	China (Qinghai-Tibet Plateau)	***Permafrost area:*** Decrease by <19% (20-50 years since 1996), Decrease by 58% (2099)	+1°C in air temp. in 30 years since 1996/HADCM2/20-50 years since 1996, 2099 (1996)	Results of Li & Cheng (1999) after Cheng & Wu (2007)
	China (Tibetan Plateau)	***Alpine vegetation:*** Most replaced by forest and shrubland	A1B/Pattern-scaled output of multiple models/2070-2099 (1931-1960)	Wang *et al*., 2013
	China (Huang-Hai Plain in northeast China)	***Winter wheat yield:*** Increase by 0.2 Mg/ha (2015-45), Increase by 0.8 Mg/ha (2070-99)	A2, B2/HadCM3/2015-45,2070-99 (1961-90)	Thomson *et al*., 2006
	China (Huang-Huai-Hai (3H) Plain)	***Wheat-maize relative yield change (RYC):*** a. +2ºC & +5ºC in temp., +15 & -30% in prec., 500 & 700 ppmv CO_2: Decreased on average by -10.33%. b. a. with CO_2 fertilization: +4.46±14.83% (2ºC), -5.78±25.82% (5ºC). Base year: 1996-2004.		Liu *et al*., 2010
	South Korea (Han, Nakdong, Gum, Sumjin, Youngsan River Basin)	***Runoff:*** Four major river basins decrease 10% by 2030	A2/ ECO-G (MM5)/ 2001-30, 2016-45 (1961-2001)	Chang *et al*., 2007
	South Korea	***Paddy irrigation requirements:*** Decrease by 1-8%	A2, B2/HadCM3(RCMs)/ 2010-2039, 2040-2069, 2070-2099 (1961-90)	Chung *et al*., 2011
		Volumetric irrigation demand: Decrease by 4-10%		
	South Korea (Soyang, Chungju, Daecheong Basins)	***Annual mean streamflow:*** Reduced by 7.6%	2×CO_2/YONU GCM (WGEN)/ 2031-50 (1961-80)	Kim *et al*., 2007
	China, Taiwan province (Upstream catchment of Shihmen reservoir)	***Runoff:*** Future runoff may be higher during wet season and lower during dry season.	A2, B2/CCSR, CGCM2, CSIRO, ECHAM4, GFDL, HADCM3/2010-39; 2040-69; 2070-99 (1973-2000)	Yu & Wang, 2009
	China (Taiwan province)	***Annual renewable water resource:*** Drop by 12.3%	A1B/JAM/MRI TL 959L60/2080-99 (1949-2000)	Tsai & Huang 2012; Li *et al*., 2010
		Water resource condition for Five levels: good (L1), good (L2), fair(L3), poor (L4), very poor (L5): No change in northern and eastern parts with L2; visibly deteriorate in southern part with L3 to L4; central part will be L4	A1B/ JAM/MRI TL 959L60/2080-99 (1979-98)	Tsai, et al., 2011
North Asia	Russia, East of Urals (Siberia)	***Tundra area:*** Decrease by 93% as result of boreal forest expansion	+1% GHG per year/HADCM3 (GGa1)/2090-2100 (1964)	Tchebakova *et al.*, 2010
		Steppe area: Increase by 27%		
	Russia, East of Urals (Asian Russia)	***Tundra area:*** Decrease by 3% as result of boreal forest expansion	+1°C in annual mean global surface temp./ECHAM4/OPYC3, HadCM3a, IAP RAS CM/Late 2030s - early 2050s (1961-90)	Golubyatnikov & Denisenko, 2007
		Steppe area: Decrease by < 65%		
	Russia, East of Urals (Asian Arctic)	***Coast recession rate:*** Increase by 1.5- to 2.6-fold	+2°C in annual mean global surface temp. over 21st C., /2100 (c. 2000)	Pavlidis *et al.*, 2007
	Russia, East of Urals (Arctic)	***Ice-dependent mammals*:** Population declines in some species	Various/Various/21st C.	Kovacs *et al*., 2011
	Russia (East of Urals)	***Frequency of shortfalls:*** +3-4 years/decade in 2070s	A2, B2/ECHAM, HadCM3/2070s (1961-90)	Alcamo *et al*., 2007
South Asia	India(All)	***Forests:*** 34-39% of forests to change forest type	A2, B2/HadRM3/2085 (1931-60)	Chaturvedi *et al*., 2011
	India (Indo-Gangetic Plains,	***Sorghum winter grain yield:*** Reduced by up to 7% by 2020, up to 11% by	A2a/HadCM3/2020, 2050, 2080 (1970-95)	Srivastava *et al*., 2010

	Indore, Hyderabad, Dharwad)	2050 and up to 32% by 2080		
	Pakistan(Swat & Chitral districts)	***Wheat yield:*** -7% & -24% (Swat district), +14% & -23% (Chitral district).	1.5 & 3°C in temp./ (1976-2000)	Hussain & Mudasser, 2007
Southeast Asia	Indonesia (Java & Bali)	***Date of rice planting:*** Shift with marked increase in probability of a 30-day delay in monsoon onset in 2050	A2, B1/Ensamble/2050 (1979-2004)	Naylor *et al*., 2007
West Asia	Iran (all)	***Deep aquifer recharge:*** Decreases by 50-100% in groundwater recharge in earstern	A1B; B1; A2/CGCM 3.1/2010-40, 2070-2100 (1980-2002)	Abbaspour *et al*., 2009
	Jordan (Upper Jordan; Wadi Faynan)	***Stream flows, flood flow and numbers:*** Decrease by 12%	A2/(HadRM3)/ 2071-2100 (1961–1990)	Wade *et al*., 2010
	Jordan (Yarmouk basin)	***Wheat and barley yield:*** a. Reduction of rainfall by 10-20%: - 4 to -8% (barley), -10 to -20% (wheat). b. Increase of rainfall by 10–20%: +3 to +5% (barley), +9 to +18% (wheat). c. Increase of air temp. by 1, 2, 3, 4°C: +14%, +28%, +38%, +46% (barley), +17%, +4%, +43%, +113% (wheat)	DSSAT/CSIROMK3, ECHAM5OM, HADGEM1/2050 (1960–2005)	Al-Bakri *et al*., 2010
Eastern Mediterranean and Middle East region		***Internal water resource:*** Decreases from 464 to 419 and 412km^3	A1B /HadCM3 (PRECIS)/2040-69, 2070-99 (1961-90)	Chenoweth *et al*., 2011
		Runoff: -9.5% & -10% (Tigris-Euphrates River), -22% & -30% (Jordan River)		
North Asia, East Asia, Central Asia	Asian Russia, China, Mongolia, Kazakhstan (Permafrost area in Asia)	***Permafrost degradation:*** Spread from southern and low-altitude margins, advancing northwards and upwards	Multiple scenarios/Multiple GCMs/21st C.	Multiple references, see section 24.4.2.3.
North, East Asia	Asian Russia, China (Siberia and Tibet)	***Permafrost distribution:*** Permafrost will remain only in Central and Eastern Siberia and in part of Tibet	A1B, A2/IAP RAS CM/Late 21st C.	Eliseev *et al.*, 2009
West, South, Southeast Asia (all countries with tropical coasts)		***Coral health:*** Large declines in structure and diversity	Several/Several/2050	Hoegh-Guldberg, 2011; Burke *et al*., 2011
Asia		***Poverty:*** Negative impact on rice crop, increase in food price and cost of living, increased poverty, projections for 2030 by GTAP Model under three scenarios resulting low, medium and high productivity		Hertel *et al*., 2010
Central, East, South, Southeast Asia (Tibet/Himalayas)		***Livelihoods:*** Loss of livelihoods to indigenous people from declining alpine biodiversity		Salick *et al*., 2009; Xu *et al*., 2009

Table 24-7: Summary of adaptation options for agriculture in Asia.

Crop	Country/ Regions	Recommended/ Potential Adaptation strategies	Benefits/ Co-Benefits	References
Wheat	General	Conservation agriculture (reductions in tillage, surface retention of adequate crop residues, and diversified, economically viable crop rotations)	Improve rural incomes and livelihoods by reducing production costs, managing agroecosystem productivity and diversity more sustainably, and minimizing unfavorable environmental impacts	Ortiz *et al.*, 2008
Wheat	Pakistan	Development of short duration and high yield varieties of wheat.	Can withstand climatic anomalies expected in future	Hussain & Mudasser 2007
Wheat	Indo- Gangetic Plains, India	Development of heat-tolerant wheat germplasm, as well as cultivars.	Better adapted to heat and conservation agriculture	Ortiz et al., 2008
Barley; wheat	Jordan	Soil water conservation. Selection of drought tolerant genotypes with shorter growing seasons.	Increase available water to crop	Al-Bakri *et al*., 2010
Sorghum	India	Changing variety and sowing date	Reduce impacts on monsoon sorghum to about 10%, 2% and 3% in 2020 scenario. Reduced impacts on winter crop to 1–2% in 2020, 3–8% in 2050 and 4–9% in 2080.	Srivastava *et al.*, 2010
Rice	Sri Lanka	Traditional approaches for resolving water stress, such as increasing water use efficiency, water harvesting and/or reducing cropped areas. Earlier planting and shorter duration varieties to avoid impacts of less rainfall in January and February.		De Silva *et al.*, 2007.
Rice	China	Shifts in planting dates and automatic application of irrigation and fertilization. Selection for more temperature-tolerant cultivars and later-maturing cultivars to take advantage of longer growing seasons		Tao *et al.*, 2008
Corn	China	Using high-temperature sensitive varieties Early planting, fixing variety growing duration, and late planting	Using high-temperature sensitive varieties, maize yield could averagely increase by 1.0-6.0%, 9.9-15.2%, and 4.1-5.6%, by adopting adaptation options of early planting, fixing variety growing duration, and late planting, respectively	Tao & Zhang, 2010
General	India	Water harvesting		Kelkar *et al*., 2008
General	South Asia	Increasing livestock production relative to crops Selection of crop varieties Livelihood diversification		Morton, 2007
General	Central Asia	Replacement of existing network of open irrigation canals by more efficient drip irrigation systems Development of early warning systems, such as drought forecast, pest and epidemic disease forecasts, and water quality monitoring systems.	Could significantly reduce evaporative water loss, while simultaneously improving crop productivity, reducing soil salinization, and decreasing risks of water contamination and transmission of vector-borne and waterborne diseases.	Lioubimtseva & Henebry, 2009
General	West Asia	Changing of cropping systems and patterns, switching from cereal-based systems to cereal–legumes and diversifying production systems into higher value and greater water use efficient options. Using supplementary irrigation systems, more efficient irrigation practices and adaptation and adoption of existing and new water harvesting technologies. Development of more drought and heat tolerant germplasm using traditional and participatory plant breeding methodologies and better predictions of extreme climatic events.		Thomas, 2008
General	Russia	Crop substitution Diversification of crops Expanding irrigated agricultural areas Strategic food reserves, Improving management, Monitoring and early warning systems, Food imports from abroad.		Alcamo *et al.*, ,2007,
General	Philippines	Crop diversification; change of crop varieties, use of water conservation pratices		Peras *et al.*, 2008; Lasco *et al.*, 2011
General	General	Cultivars with multiple resistance to insects and diseases		Sharma *et al.*, 2010

Table 24-8: Summary of adaptation options for securing livelihoods in Asia.

Aspect/ Issues	Country/ Regions	Recommended/ Potential Adaptation strategies	Benefits/ Co-Benefits	References
Delay and shortfall in rainfall	Indonesia	Access to credit and public works project	Able to protect food expenditure in the face of weather shocks	Skoufias *et al.*, 2011
General (droughts, floods etc)	General	Weather index insurance, cattle insurance, seed banks, credit facilities, assisted migration, cash for work	Poverty cantered adaptation, creation of assets and access to resources	Barret *et al.*, 2007; Tanner and Mitchel, 2008; Jarvis *et al.*, 2011
General	General	Assisted migration	Build financial, social and human capital	Barnett and Webber, 2010
General	Vietnam	Yield growth and improving agriculture labour productivity	Rural poverty reduction, livelihood diversification	Janvry and Sadoulet, 2010
Droughts and floods	Philippines	Bundling of improved varieties and agronomic practices and combination of production and market support	Economic benefits and social learning	Acosta-Michlik & Espaldon, 2008
General	Asia	Community based adaptation	Capture information at the grassroots, help integrating disaster risk reduction, development, and climate change adaptation, connect local communities and outsiders, and addresses the location specific nature of adaptation.	Aalst et al., 2008; Heltberg *et al.*, 2010; Rosegrant, 2011
General	Asia	Forest management	Resilient livelihoods, buffer from shocks	Chhatre & Agrawal, 2009
General	Asia	Securing rights to resources, community forest tenure rights	Resilient livelihood benefits to the poor indigenous and traditional people	Macchi *et al.*, 2008; Angelsen, 2009
Biodiversity loss	Tibet	Greater involvement of traditional and indeginous people in climate change adaptation decision making	Indigenous knowledge from the years of living in close harmony with nature	Byg & Salick, 2009; Salick *et al.*, 2009

Table 24-9: Recent publications on central Asia glaciers changes

Region	Period	Initial area (km^2)	Area change, km^2 (%)	References
Akshiirak (Inner Tien Shan)	1977-2001	406.8	-93.6(-23)	Khromova *et al.*, 2003
Akshiirak (Inner Tien Shan)	1977-2003	406.8	-35.15 (-8.6)	Aizen *et al.*, 2007
ZailiyskiyAlatau (Northern Tien Shan)	1955-1990	287.3	-81.8 (-29)	Vilesov & Uvarov, 2001
ZailiyskiyAlatau (Northern Tien Shan)	1979-1999	198.37	-34.2 (-17.3)	Bolch, 2007
Sokoluk R. basin, Kirgizkiy range (Northern Tien Shan)	1963-1986 1986-2000	31.7 27.5	-4.2 (-13.3) -4.7 (-17.1)	Niederer *et al.*, 2008
Gl.No. 1, Urumqi (Eastern Tien Shan)	1962-2003	1.94	-0.24 (-12.4)	Ye *et al.*, 2005
Terskey-Alatoo (IssikKul Lake Basin, Northern Tien Shan)	1971-2002	245	-18 (-8)	Narama *et al.*, 2006
Aksu R. basin (Kokshaaltau, Central Tien Shan)	1963-1999	1760	-58.6 (-3.3)	Li *et al.*, 2006
Kaidu R. basin (Tarim R. Basin ,Central Tien Shan)	1963-2000	333	-38.5 (-11.6)	Liu *et al.*, 2005
Central Tien Shan, Chinese territory	1960s- 1999	2093.8	-96.3 (-4.6)	Ding *et al.*, 2006
Tien Shan (all mountain system) Altai (all mountain system)	1960s-2008 1960s-2008	17,679 2,169	-1,172 (6.6%) -127 (5.8%)	Aizen, 2011
Pamir (Amu Darýa R. Basin)	1960s-2008	14,095	-671 (4.8%)	Aizen, 2011

Figure 24-1: The land and territories of 51 countries/regions.

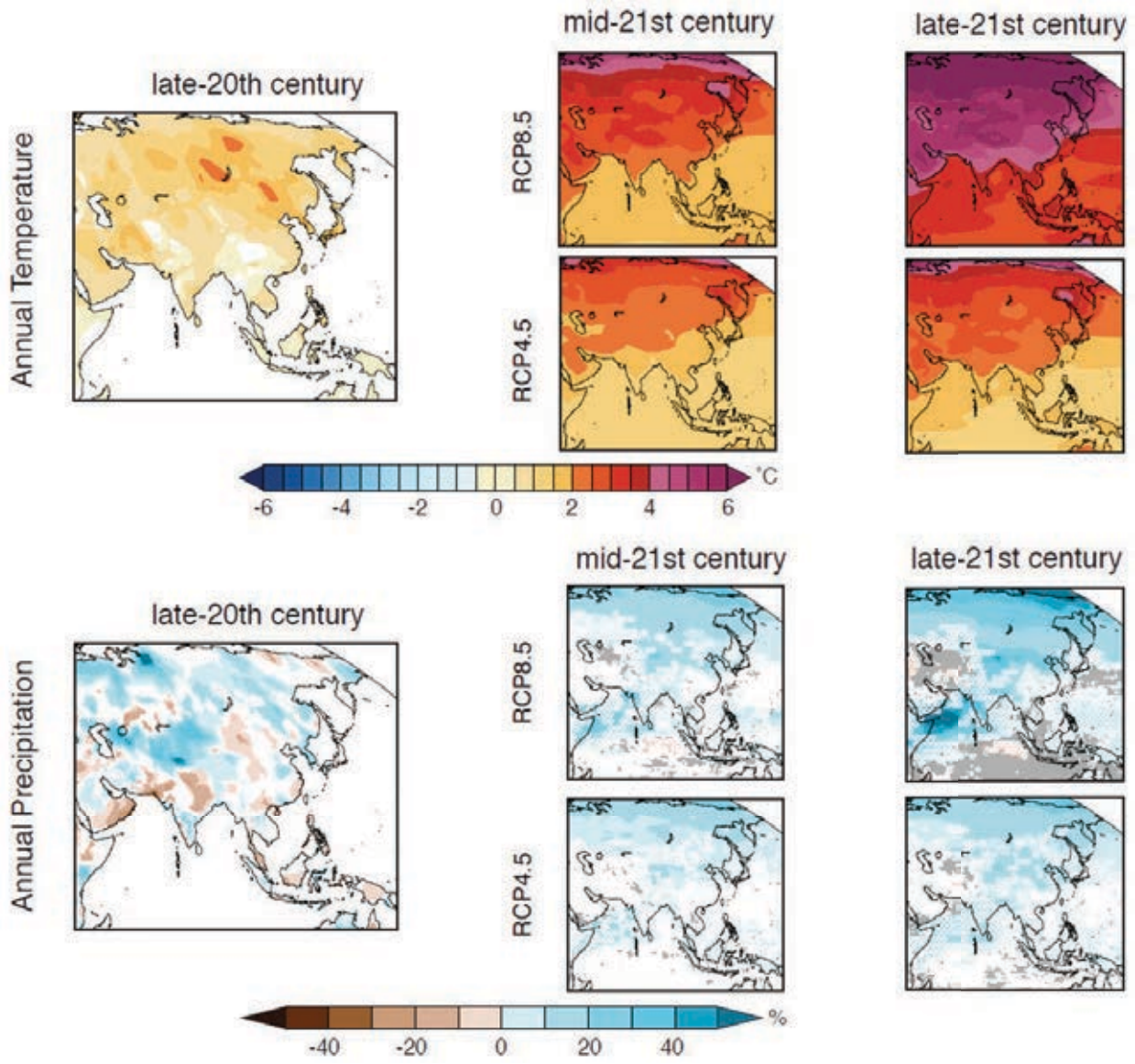

Figure 24-2: Change in annual temperature and precipitation in Asia. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

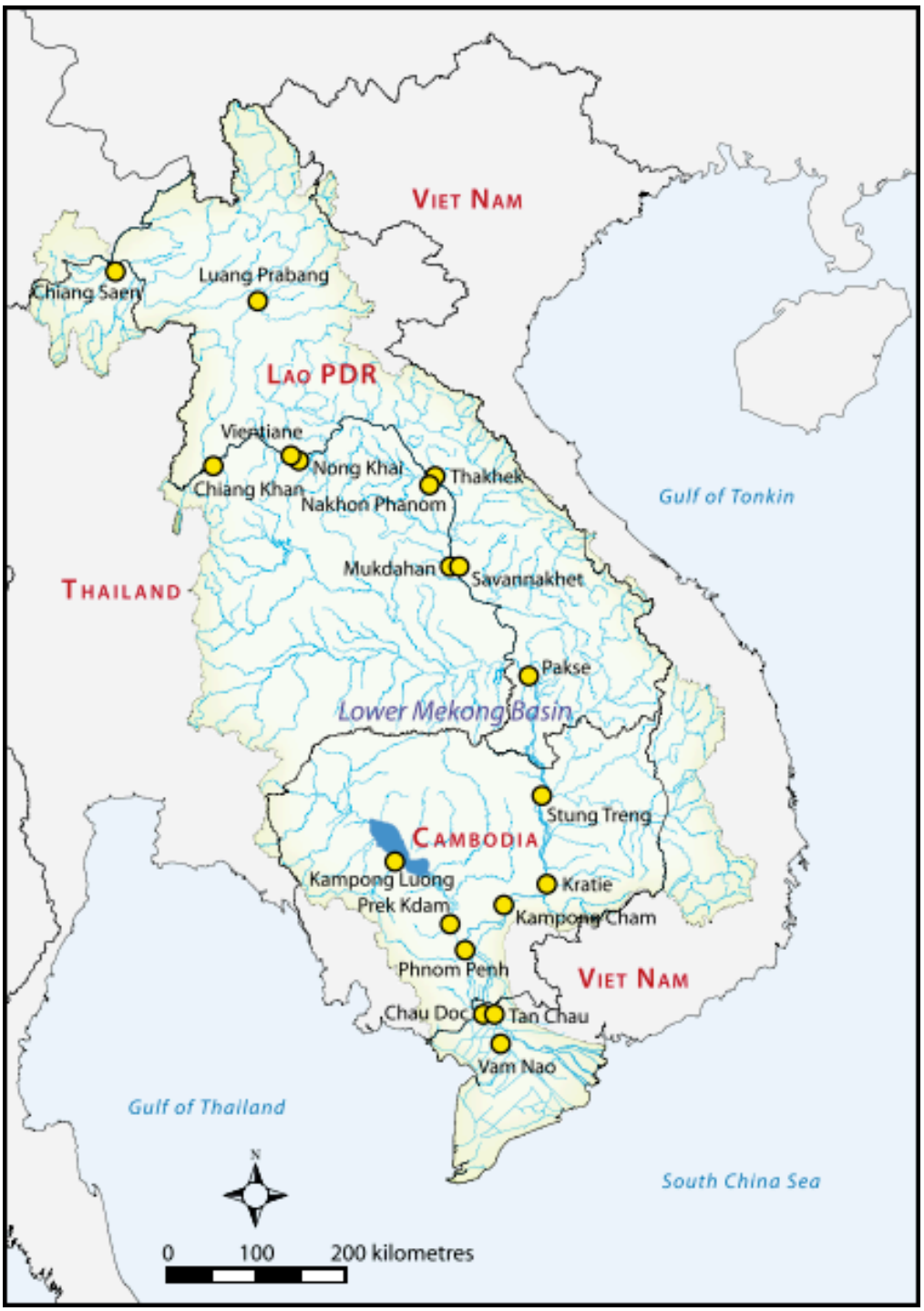

Figure 24-3: Map of Lower Mekong Basin from Mekong River Commission Technical Paper No. 24, 2009 (MRC, 2009).

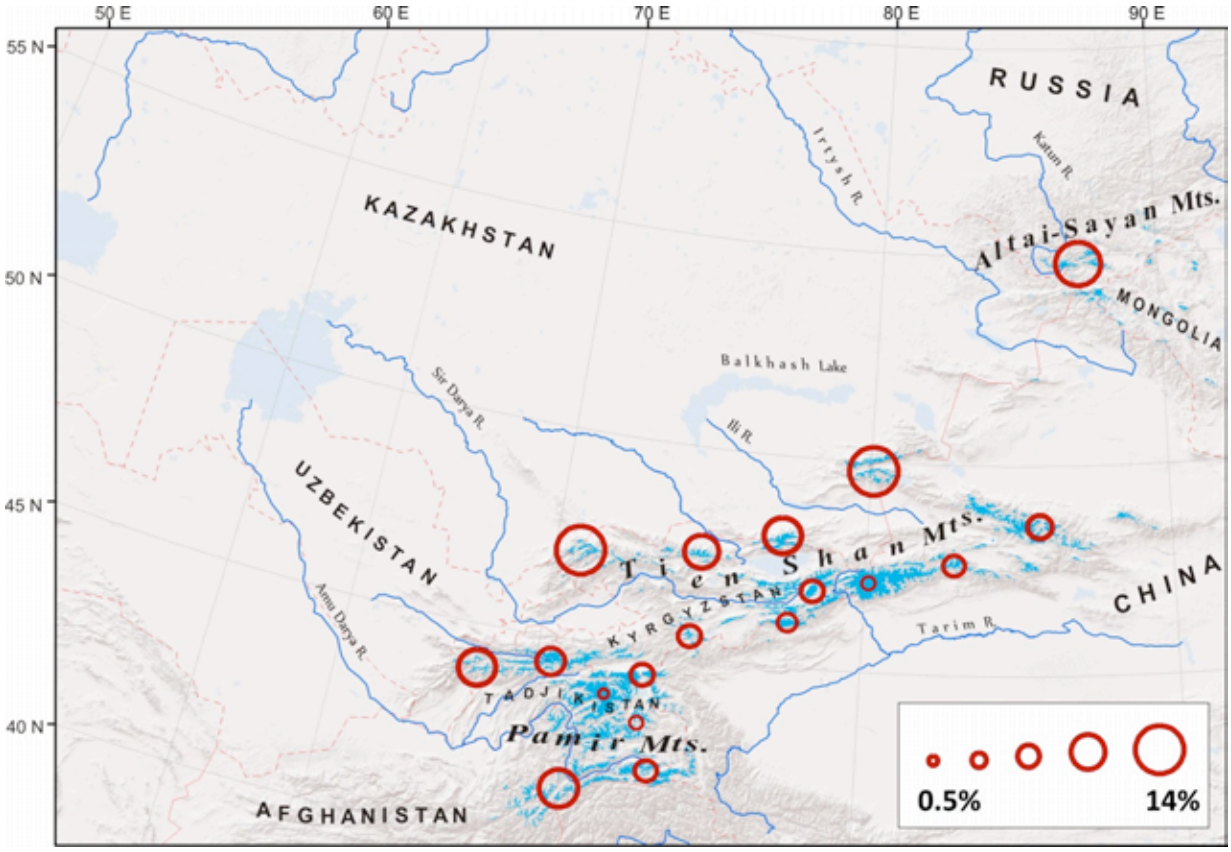

Figure 24-4: The difference in losses of glacier area in Altai-Sayan, Pamir and Tien Shan. Remote sensing data analysis from 1960s (Corona) through 2009 (Landsat, ASTER and Alos Prism).

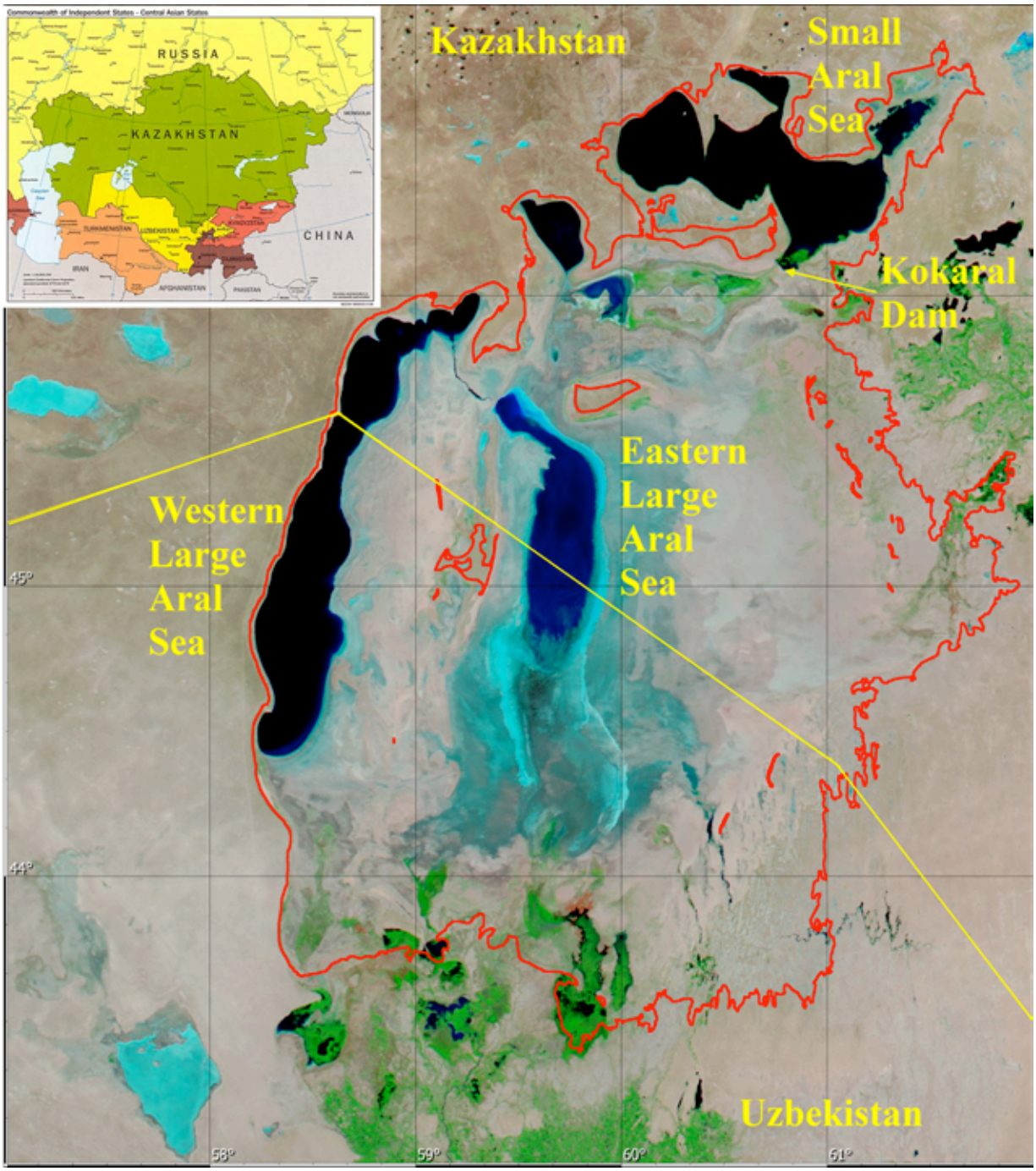

Figure 24-5: The satellite view of the Aral Sea acquired on 7 September 2012 from MODIS-Aqua. Image courtesy by A.G. Kostianoy (P.P. Shirshov Institute of Oceanology, Moscow, Russia) and D.M. Solovyov (Marine Hydrophysical Institute, Sevastopol, the Ukraine), based on the LAADS Web, NASA-Goddard Space Flight Center data (http://ladsweb.nascom.nasa.gov/). The red line indicates the Aral Sea coastline back in 1960. The yellow line indicates the border between Kazakhstan and Uzbekistan.

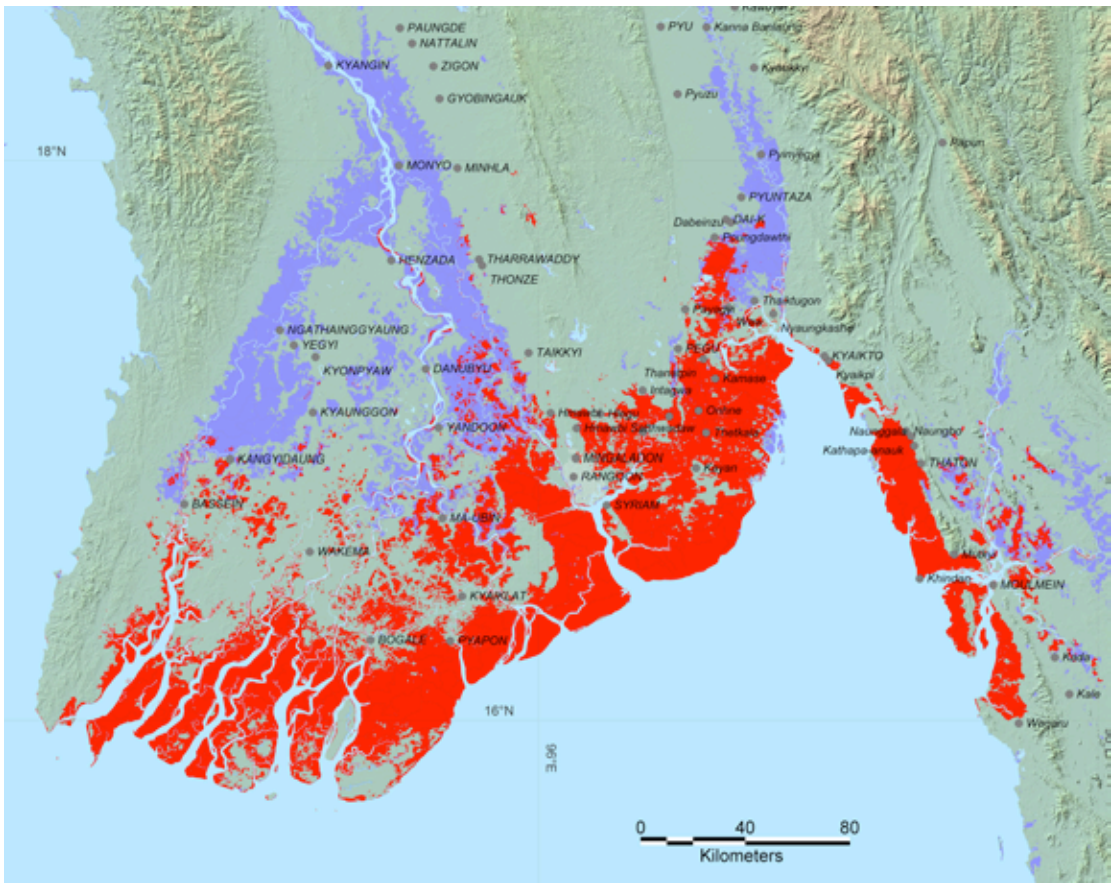

Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. (From Brakenridge *et al.*, 2012).

Chapter 25. Australasia

Coordinating Lead Authors
Andy Reisinger (New Zealand), Roger Kitching (Australia)

Lead Authors
Francis Chiew (Australia), Lesley Hughes (Australia), Paul Newton (New Zealand), Sandra Schuster (Australia), Andrew Tait (New Zealand), Penny Whetton (Australia)

Contributing Authors
Jon Barnett (Australia), Susanne Becken (New Zealand), Paula Blackett (New Zealand), Sarah Boulter (Australia), Andrew Campbell (Australia), Daniel Collins (New Zealand), Jocelyn Davies (Australia), Keith Dear (Australia), Stephen Dovers (Australia), Kyla Finlay (Australia), Bruce Glavovic (New Zealand), Donna Green (Australia), Don Gunasekera (Australia), Simon Hales (New Zealand), John Handmer (Australia), Garth Harmsworth (New Zealand), Alistair Hobday (Australia), Mark Howden (Australia), Graeme Hugo (Australia), David Jones (Australia), Sue Jackson (Australia), Darren King (New Zealand), Miko Kirschbaum (New Zealand), Jo Luck (Australia), Jan McDonald (Australia), Kathy McInnes (Australia), Yiheyis Maru (Australia), Johanna Mustelin (Australia), Barbara Norman (Australia), Grant Pearce (New Zealand), Susan Peoples (New Zealand), Ben Preston (USA), Joseph Reser (Australia), Penny Reyenga (Australia), Mark Stafford-Smith (Australia), Xiaoming Wang (Australia), Leanne Webb (Australia)

Review Editors
Blair Fitzharris (New Zealand), David Karoly (Australia)

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Executive Summary

The regional climate is changing (***very high confidence***). The region continues to demonstrate long term trends toward higher surface air and sea-surface temperatures, more hot extremes and fewer cold extremes, and changed rainfall patterns. Over the past 50 years, increasing greenhouse gas concentrations have contributed to rising regional average temperature *(high confidence)* and changes to rainfall in far south-west Australia (*medium confidence*). [25.2, Table 25-1]

Warming is projected to continue through the 21st century (*virtually certain*) along with other changes in climate. Warming is expected to be associated with more frequent hot extremes and less frequent cold extremes (*high confidence*), and increasing extreme rainfall and flood risk in many locations (*medium confidence*). Annual average rainfall is expected to decrease in south-western Australia (*high confidence*) and elsewhere in southern Australia and the north-east South Island and northern and eastern North Island of New Zealand, and to increase in other parts of New Zealand (*medium confidence*). Tropical cyclones are projected to increase in intensity but decrease in numbers (*low confidence*), and fire weather is projected to increase in most of southern Australia (*high confidence*) and many parts of New Zealand (*medium confidence*). Regional sea level rise will *very likely* exceed the historical rate (1971-2010), consistent with global mean trends. [25.2, Table 25-1, Box 25-6, WGI 13.6]

Uncertainty in projected rainfall changes remains large for many parts of Australia and New Zealand, which creates significant challenges for adaptation. For example, projections for average annual runoff in far south-eastern Australia range from little change to a 40% decline for 2°C global warming. The dry end of these scenarios would have severe implications for agriculture, rural livelihoods, ecosystems and urban water supply, and would increase demands for transformative adaptation (*high confidence*). [25.2, 25.5.1, 25.6.1, 25.7.2, Box 25-2, Box 25-5]

Recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (*very high confidence*), and the frequency and/or intensity of such events is projected to increase in many locations (*medium* to *high confidence*). For example, high sea surface temperatures have repeatedly bleached coral reefs in north-eastern Australia (since the late 1970s) and more recently in western Australia. Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011); the Victorian heat wave (2009) increased heat-related morbidity and caused 374 excess deaths, and intense bushfires destroyed over 2,000 buildings and led to 173 deaths; widespread drought in south-east Australia (1997-2009) and many parts of New Zealand (2007-2009) resulted in economic losses (approximately A$7.4b in south-east Australia in 2002-03 and NZ$3.6b in direct and off-farm output in 2007-09) and mental health problems in some areas of Australia. [Table 25-1, 25.6.2, 25.8.1, Box 25-5, Box 25-6, Box 25-8]

Without adaptation, further changes in climate, atmospheric CO_2 and ocean pH are projected to affect water resources, coastal ecosystems, infrastructure, agriculture, and biodiversity substantially (*high confidence*). Freshwater resources are projected to decline in far south-west and far south-east mainland Australia (*high confidence*) and for rivers originating in the eastern and northern parts of New Zealand (*medium confidence*); rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure and housing; rainfall changes and rising temperatures will shift agricultural production zones; and many endemic species will suffer from range contractions and some may face local or even global extinction. [25.5.1, 25.6.1, 25.6.2, 25.7.1, 25.7.2, 25.7.4, Box 25-1, Box 25-5, Box 25-8]

Some sectors in some locations have the potential to benefit from projected changes in climate and increasing atmospheric CO_2 (*high confidence*). Examples include reduced morbidity from winter illnesses and reduced energy demand for winter heating in New Zealand and southern parts of Australia, and forest growth in cooler regions except where soil nutrients or rainfall are limiting. Spring pasture growth in cooler regions would also increase and be beneficial for animal production if it can be utilized. [25.7.1, 25.7.2, 25.7.4, 25.8.1]

Adaptation is already occurring and adaptation planning is becoming embedded in planning processes, albeit mostly at the conceptual rather than implementation level (*high agreement, robust evidence*). Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g. greening cities and recycling water), are already being implemented. Planning for sea-level rise and, in Australia, reduced water availability, is becoming widely adopted, although implementation of specific policies remains piecemeal, subject to political changes, and open to legal challenges. [25.4, Box 25-1, Box 25-2, Box 25-9]

Adaptive capacity is generally high in many human systems, but implementation faces major constraints especially for transformative responses at local and community levels (*high confidence*). Efforts to understand and enhance adaptive capacity and adaptation processes have increased since AR4, particularly in Australia. Constraints on implementation arise from: uncertainty of projected impacts; limited financial and human resources to develop and implement effective policies and rules; limited integration of different levels of governance; lack of

binding guidance on principles and priorities; different values and beliefs relating to the existence of climate change, objects and places at risk; and, attitudes towards risk. [25.4, 25.10.3, Box 25-1]

Indigenous peoples in both Australia and New Zealand have higher than average exposure to climate change due to a heavy reliance on climate-sensitive primary industries and strong income and social connections to the natural environment, and face particular constraints to adaptation (*medium confidence*). Social status and representation, health, infrastructure and economic issues, and engagement with natural resource industries constrain adaptation and are only partly offset by intrinsic adaptive capacity (*high confidence*). Some proposed responses to climate change may provide economic opportunities, particularly in New Zealand related to forestry. Torres Strait communities are vulnerable even to small sea level rises (*high confidence*). [25.3, 25.8.2]

We identify eight *regional key risks* during the 21st century based on the severity of potential impacts for different levels of warming, uniqueness of the systems affected, and adaptation options (*high confidence*). These risks differ in the degree to which they can be managed via adaptation and mitigation, and some are more likely to be realized than others, but all warrant attention from a risk-management perspective.

- Some potential impacts can be delayed but now appear very difficult to avoid entirely, even with combined globally effective mitigation and planned adaptation:
  - ***significant change in community structure of coral reef systems in Australia***, driven by increasing sea-surface temperatures and ocean acidification; the natural ability of reefs to adapt to projected changes is limited [Box CC-CR, 25.6.2, 30.5]
  - ***loss of montane ecosystems and some endemic species in Australia***, driven by rising temperatures, increased fire risk and drying trends; fragmentation of landscapes, limited dispersal and evolutionary capacity limit adaptation options [25.6.1]
- Some impacts have the potential to be severe but can be moderated or delayed significantly by globally effective mitigation combined with adaptation, with an increasing need for transformative adaptation for greater rates and magnitude of change:
  - ***increased frequency and intensity of flood damage to settlements and infrastructure in Australia and New Zealand***, driven by increasing extreme rainfall although the amount of change remains uncertain; in many locations, continued reliance on increased protection alone would become progressively less feasible [Table 25-1, 25.4.2, 25.10.3, Box 25-8]
  - ***systematic constraints on water resource use in southern Australia***, driven by rising temperatures and reduced cool-season rainfall; integrated responses encompassing management of supply, recycling, water conservation and increased efficiency across all sectors are available but face implementation constraints [25.2, 25.5.1, Box 25-2]
  - ***increasing morbidity, mortality and infrastructure damages during heat waves in Australia***, resulting from increased frequency and magnitude of extreme temperatures; vulnerable populations include the elderly, children and those with existing chronic diseases; ageing trends and prevailing social dynamics constrain effectiveness of adaptation responses [25.8.1]
  - ***increased damages to ecosystems and settlements, economic losses and risks to human life from wildfires in most of southern Australia and many parts of New Zealand***, driven by drying trends and rising temperatures; building codes, design standards, local planning mechanisms and public education can assist with adaptation and are being implemented in regions that have experienced major events [25.2, Table 25-1, 25.6.1, 25.7.1, Box 25-6]
- Some potential impacts have a low or currently unknown probability but cannot be ruled out entirely even under mitigation scenarios; these impacts would present major challenges if realized:
  - ***widespread damages to coastal infrastructure and low-lying ecosystems in Australia and New Zealand* if *sea level rise exceeds 1m***; managed retreat is a long-term adaptation strategy for human systems but options for some natural ecosystems are limited due to the rapidity of change and lack of suitable space for inland migration. Risks from sea level rise *very likely* continue to increase beyond 2100 even if temperatures are stabilised. [AR5 *WGI 13.ES;* Box 25-1, Table 25-1, 25.4.2, 25.6.1-2]
  - ***significant reduction in food production in the Murray-Darling Basin, far south-eastern Australia and some eastern and northern areas of New Zealand* if *scenarios of severe drying are realised;*** more efficient water use, allocation and trading would increase the resilience of systems in the near term but

cannot prevent significant reductions in agricultural production and severe consequences for ecosystems and some rural communities at the dry end of the projected range [25.2, 25.5.1, 25.7.2, Box 25-5]

Significant synergies and trade-offs exist between alternative adaptation responses, and between mitigation and adaptation responses; interactions occur both within Australasia and between Australasia and the rest of the world (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy and biodiversity, but tools to understand and manage these interactions remain limited. Flow-on effects from climate change impacts and responses outside Australasia have the potential to outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*), but they remain amongst the least explored issues. [25.7.5, 25.9.1, 25.9.2, Box 25-10]

Understanding of future vulnerability of human and mixed human-natural systems to climate change remains limited due to incomplete consideration of socio-economic dimensions (*very high confidence*). Future vulnerability will depend on factors such as wealth and its distribution across society, patterns of ageing, access to technology and information, labour force participation, societal values, and mechanisms and institutions to resolve conflicts. These dimensions have received only limited attention and are rarely included in vulnerability assessments, and frameworks to integrate social and cultural dimensions of vulnerability with bio-physical impacts and economic losses are lacking. In addition, conclusions for New Zealand in many sectors, even for bio-physical impacts, are based on limited studies that often use a narrow set of assumptions, models and data and hence have not explored the full range of potential outcomes. [25.3, 25.4, 25.11]

25.1. Introduction and Major Conclusions from Previous Assessments

Australasia is defined here as lands, territories, offshore waters and oceanic islands of the exclusive economic zones of Australia and New Zealand. Both countries are relatively wealthy with export-led economies. Both have Westminster-style political systems and have a relatively recent history of non-indigenous settlement (Australia in the late 18th, New Zealand in the early 19th century). Both retain significant indigenous populations.

Principal findings from the IPCC Fourth Assessment Report (AR4) for the region were (Hennessy *et al*., 2007):

- Consistent with global trends, Australia and New Zealand had experienced warming of 0.4 to 0.7°C since 1950 with changed rainfall patterns and sea-level rise of about 70 mm across the region; there had also been a greater frequency and intensity of droughts and heat waves, reduced seasonal snow cover and glacial retreat.
- Impacts from recent climate changes were evident in increasing stresses on water supply and agriculture, and changed natural ecosystems; some adaptation had occurred in these sectors but vulnerability to extreme events such as fire, tropical cyclones, droughts, hail and floods remained high.
- The climate of the 21st century would be warmer (*virtually certain*), with changes in extreme events including more intense and frequent heat waves, fire, floods, storm surges and droughts but less frequent frost and snow (*high confidence*), reduced soil moisture in large parts of the Australian mainland and eastern New Zealand but more rain in western New Zealand (*medium confidence*).
- Significant advances had occurred in understanding future impacts on water, ecosystems, Indigenous people and health together with an increased focus on adaptation; potential impacts would be substantial without further adaptation, particularly for water security, coastal development, biodiversity, and major infrastructure, but impacts on agriculture and forestry would be variable across the region, including potential benefits in some areas.
- Vulnerability would increase mainly due to an increase in extreme events; human systems were considered to have a higher adaptive capacity than natural systems.
- Hotspots of high vulnerability by 2050 under a medium emissions scenario included:
  - significant loss of biodiversity in areas such as alpine regions, the Wet Tropics, the Australian south-west, Kakadu wetlands, coral reefs and sub-Antarctic islands;
  - water security problems in the Murray-Darling basin, south-western Australia and eastern New Zealand;
  - potentially large losses in areas of rapid coastal development in south-eastern Queensland and in New Zealand from Northland to the Bay of Plenty.

25.2. Observed and Projected Climate Change

Australasia exhibits a wide diversity of climates including moist tropical monsoonal, arid and moist temperate, including alpine conditions. Key climatic processes are the Asian-Australian monsoon and the southeast trade winds over northern Australia, and the subtropical high pressure belt and the mid-latitude storm tracks over southern Australia and New Zealand. Tropical cyclones also affect northern Australia, and, more rarely, the northernmost areas of New Zealand. Natural climatic variability is very high in the region, especially for rainfall and over Australia, with the El Nino-Southern Oscillation (ENSO) being the most important driver (McBride and Nicholls, 1983; Power *et al.*, 1998). The southern annular mode, Indian Ocean Dipole and the Pacific Decadal Oscillation are also important regional drivers (Thompson and Wallace, 2000; Cai *et al.*, 2009b). This variability poses particular challenges for detecting and projecting anthropogenic climate change and its impacts in the region. For example, changes in ENSO in response to anthropogenic climate change are uncertain (AR5 WGI Ch14) but could significantly influence rainfall and temperature extremes, droughts, fire danger, tropical cyclones, marine conditions and glacial mass balance.

Understanding of observed and projected climate change has received significant attention since AR4, particularly in Australia, with a focus on better understanding the causes of observed rainfall changes and more systematic analysis of projected changes from different models and approaches. Climatic extremes have also been a research focus. Table 25-1 presents an assessment of this body of research for observed trends and projected changes for a range of climatic variables (including extremes) relevant for regional impacts and adaptation, including examples of the magnitude of projected change where possible. Most studies are based on CMIP3 models and SRES scenarios, but CMIP5 model results are considered where available (see also AR5 WGI Chap 14 and Atlas, WGII Chapter 21).

The region has exhibited warming to the present (*very high confidence*) and is *virtually certain* to continue to do so (Table 25-1). Observed and CMIP5-modelled past and projected future annual average surface temperatures are shown in Figures 25-1 and 25-2. For further details see WGI Atlas, Figures AI.82-85.

Changes in precipitation have been observed with *very high confidence* in some areas, such as the autumn/winter decline since 1970 in south-western Australia and, since the 1990s, in south-eastern Australia, and over 1950-2004 increases in annual rainfall in the south and west of both islands of New Zealand with decreases elsewhere. Based on multiple lines of evidence, annual average rainfall is projected to decrease with at least *medium confidence* in southern Australia and in the north-east South Island and eastern and northern North Island of New Zealand, and increase in other parts of New Zealand. The direction and magnitude of rainfall change in eastern and northern Australia remains a key uncertainty (Table 25-1).

This pattern of projected rainfall change is reflected in CMIP5 model results (Figure 25-1; WGI Atlas Figures AI 86-87). Examples of the magnitude of projected annual change from 1990 to 2090 under RCP8.5 from CMIP5 are -2±21% in the Murray Darling Basin, -5±22% in Queensland and -20±13% in south-western Australia. Changes during winter and spring are more pronounced and consistent across models in many areas (see Figure 25-3), e.g. drying in the Murray Darling Basin (-16±22%, June to August) but an increase by 15% or more in the west and south of the South Island of New Zealand (Irving *et al.*, in press). Downscaled CMIP3 model projections for New Zealand indicate a stronger drying pattern in the south-east of the South Island and eastern and northern regions of the North Island in winter and spring (Reisinger *et al.*, 2010) than seen in the raw CMIP5 data; based on similar broader scale changes this pattern is expected to hold once CMIP5 data are also downscaled (Irving *et al.*, in press).

Other projected changes of at least *high confidence* include regional increases in sea surface temperature, the occurrence of hot days, extreme rainfall, mean and extreme sea level, fire danger in southern Australia, and decreases in cold days and snow extent and depth. Although changes to tropical cyclone occurrence and that of other severe storms are potentially important for future vulnerability, regional changes to these phenomena cannot be projected with at least *medium confidence* as yet.

[INSERT FIGURE 25-1 HERE
Figure 25-1: Observed and projected change in annual temperature and precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

[INSERT FIGURE 25-2 HERE
Figure 25-2: Observed and simulated variations in past and projected future annual average temperature over land areas of Australia (left) and New Zealand (right). Black lines show several estimates from measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Chapter 21.]

[INSERT FIGURE 25-3 HERE
Figure 25-3: Projected CMIP5 multi-model mean change in rainfall for 2080-2099 relative to 1980-1999, under RCP 8.5. Dots [carets] indicate where the models agree (>90% red; >67% black) that there will [will not] be a substantial increase (>10%) or decrease (< -10%). White areas indicate where the models agree (> 67%) that there will be a substantial change in rainfall (larger in magnitude than 10%) however <67% agree on the direction of this substantial change (Figure from Irving *et al*., in press).]

[INSERT TABLE 25-1 HERE
Table 25-1: Observed and projected changes in key climate variables, and (where assessed) the contribution of human activities to observed changes. For further relevant information see WGI Chapters 3, 6 (ocean changes, including acidification), 11, 12 (projections), 13 (sea level) and 14 (regional climate phenomena).]

25.3. Socio-Economic Trends Influencing Vulnerability and Adaptive Capacity

25.3.1. Economic, Demographic and Social Trends

The economies of Australia and New Zealand rely on natural resources, agriculture, minerals, manufacturing and tourism, but the relative importance of these sectors differs between the two countries. Agriculture and mineral/energy resources accounted, respectively, for 11% and 54% (Australia) and 56% and 5% (New Zealand) of the value of total exports in 2009/2010 (ABARES, 2010; Stats NZ, 2011c). Australia and New Zealand abstracted an estimated 930 and 940 m^3 of water per capita in 2007, with about half used for irrigation (OECD, 2011). Between 1970 and 2011, GDP grew by an average of 3.2% p.a. in Australia and 2.4% p.a. in New Zealand, with annual GDP per capita growth of 1.8% and 1.2%, respectively (Stats NZ, 2011a; ABS, 2012b; Stats NZ, 2012). GDP is projected to grow on average by 2.5-3.5% p.a. in Australia and about 1.9% p.a. in New Zealand to 2050 (Australian Treasury, 2010; Bell *et al*., 2010) subject to significant short-term fluctuations.

The populations of Australia and New Zealand are projected to grow significantly over at least the next several decades (*very high confidence*) due to immigration and changes in mortality and fertility (ABS, 2008; Stats NZ,

2011b); Australia's population from 22.4 million in 2011 to 31-43 million by 2056 and 34-62 million by 2101 (ABS, 2008); New Zealand's population from 4.4 million in 2011 to 4.8-6.7 million by 2061 (Stats NZ, 2011b). The number of people aged 65 and over is projected to double in the next two decades (Australian Treasury, 2010; Stats NZ, 2011b). More than 20% of Australian and New Zealand residents were born overseas (OECD, 2011). More than 85% of the Australasian population lives in urban areas and their satellite communities (Stats NZ, 2004; ABS, 2008), mostly in coastal areas (DCC, 2009; Stats NZ, 2010b). Urban concentration and depletion of remote rural areas is expected to continue (Mendham and Curtis, 2010; Stats NZ, 2010c), but some coastal non-urban spaces also face increasing development pressure (Freeman and Cheyne, 2008; Gurran, 2008).

Poverty rates and income inequality in New Zealand and Australia are in the upper half of OECD countries. Both measures increased significantly in New Zealand between the mid-1980s and mid-2000s (OECD, 2011). Measurement of poverty and inequality, however, is highly contested and anticipating future changes and effects on adaptive capacity remain difficult (Peace, 2001; Scutella *et al*., 2009).

Indigenous peoples constitute about 2% and 15% of the Australian and New Zealand populations, respectively, but are growing faster than the average and, in Australia, constitute a much higher percentage of the population in remote and very remote regions (ABS, 2009; Biddle and Taylor, 2009; ABS, 2010a; Stats NZ, 2010a). Indigenous peoples in both countries have lower than average life expectancy, income and education, implying that changes in socio-economic status and social inclusion could strongly influence their future adaptive capacity (25.8.2).

25.3.2. Use and Relevance of Socio-Economic Scenarios in Adaptive Capacity/Vulnerability Assessments

Demographic, economic and socio-cultural trends influence the vulnerability and adaptive capacity of individuals and communities (see Chapters 2, 11-13, 16). A limited but growing number of studies in Australasia have attempted to incorporate such information, e.g. changes in the number of people and percentage of elderly people at risk (Preston *et al*., 2008; Baum *et al*., 2009; Preston and Stafford-Smith, 2009; Roiko *et al*., 2012), the density of urban settlements and exposed infrastructure (Preston and Jones, 2008; Preston *et al*., 2008; Baynes *et al*., 2012), population-driven pressures on water demand (CSIRO, 2009a), and economic and social factors affecting individual coping, planning and recovery capacity (Dwyer *et al*., 2004; Khan, 2012; Khan *et al*., 2012; Roiko *et al*., 2012).

Socio-economic considerations are used increasingly to understand adaptive capacity of communities (Preston *et al*., 2008; Smith *et al*., 2008; Fitzsimons *et al*., 2010; Soste, 2010; Brunckhorst *et al*., 2011; Cradock-Henry, in press) and to construct scenarios to help build regional planning capacity (CSIRO, 2006; Frame *et al*., 2007; Pride *et al*., 2010; Pettit *et al*., 2011; Taylor *et al*., 2011). Such scenarios, however, are only beginning to be used to quantify vulnerability to climate change (except e.g. Bohensky *et al*., 2011; Baynes *et al*., 2012; Low Choy *et al*., 2012).

Apart from these emerging efforts, most vulnerability studies from Australasia make no or very limited use of socio-economic factors, consider only current conditions, and/or rely on postulated correlations between generic socio-economic indicators and climate change vulnerability. In many cases this limits confidence in conclusions regarding future vulnerability to climate change and adaptive capacity of human and mixed natural-human systems.

25.4. Cross-Sectoral Adaptation: Approaches, Effectiveness, and Constraints

25.4.1. Frameworks, Governance, and Institutional Arrangements

Adaptation to climate change is motivated by experienced and expected changes in climate but also influenced by non-climate pressures, social and cultural values, perceptions of risk, and economic and political considerations. Adaptation responses depend heavily on institutional and governance arrangements that enable decision-makers to consider climate change information (see Chapters 2, 14, 15, 16, 20; Downing, 2012).

Responsibility for development and implementation of adaptation policy in Australasia is largely devolved to local governments and, in Australia, to State governments and Natural Resource Management bodies. Federal/central

government supports adaptation mostly via provision of information, tools, legislation, policy guidance and (in Australia) support for pilot projects. A standard risk management paradigm has been promoted to embed adaptation into decision-making practices (AGO, 2006; MfE, 2008d; Standards Australia, 2012).

The Council of Australian Governments agreed a national adaptation policy framework in 2007 (COAG, 2007). This included establishing the collaborative National Climate Change Adaptation Research Facility (NCCARF) in 2008, which complements CSIRO's Climate Adaptation Flagship. The federal government supported a first-pass national coastal risk assessment (DCC, 2009; DCCEE, 2011), and reports addressing impacts and management options for natural and managed landscapes (Campbell, 2008; Steffen *et al*., 2009; Dunlop *et al*., 2012), National and World Heritage areas (ANU, 2009; BMT WBM, 2011), and indigenous and urban communities (Green *et al*., 2009; Norman, 2010). In New Zealand, the central government updated and expanded tools to support impact assessments and adaptation responses consistent with regulatory requirements (MfE, 2008a, d, c, 2010a), and revised key directions for coastal management (Minister of Conservation, 2010). No cross-sectoral adaptation policy framework or national-level risk assessments exist, but some departments commissioned high-level impacts assessments after the AR4 (e.g. on agriculture and on biodiversity; Wratt *et al*., 2008; McGlone and Walker, 2011).

Public and private sector organisations are potentially important adaptation actors but exhibit large differences in preparedness, linked to knowledge and belief about climate change, economic opportunities, external connections, size, familiarity with strategic planning and planning horizons (Gardner *et al*., 2010; Johnston *et al*., 2012; Murta *et al*., 2012; Taylor *et al*., 2012a). This creates challenges for achieving holistic societal outcomes (see also 25.7-25.9).

Several recent policy initiatives in Australia, while responding to broader socio-economic and environmental pressures, include goals to reduce vulnerability to climate variability and change. These include establishing the Murray-Darling Basin Authority to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011), removal of the interest rate subsidy during exceptional droughts (Productivity Commission, 2009), and management of bush fire risk (VBRC, 2010). These may be seen as examples of mainstreaming adaptation (Dovers, 2009), but they also demonstrate lag times in policy design and implementation and windows of opportunity presented by crises (e.g. the Millennium Drought 1997-2009, the Victorian bushfires 2009), and the challenges arising from competing interests in managing finite water resources (Botterill and Dovers, 2013; Box 25-2).

25.4.2. Constraints on Adaptation and Emerging Leading Practice Models

A rapidly growing literature since the AR4 confirms, with *high confidence,* that while the adaptive capacity of society in Australasia is generally high, there are formidable environmental, economic, informational, social, attitudinal and political constraints, especially at the community level, and for small or highly fragmented industries. Reviews of public- and private-sector adaptation plans and strategies in Australia demonstrate strong efforts in institutional capacity building, but differences in assessment methods and weaknesses in translating goals into specific policies (White, 2009; Gardner *et al*., 2010; Measham *et al*., 2011; Preston *et al*., 2011; Kay *et al*., 2013). Similarly, local governments in New Zealand to date have mostly focused on impacts and climate-related hazards but few have committed to specific climate change responses (e.g. O'Donnell, 2007; Britton, 2010; Fitzharris, 2010; HRC, 2012; KCDC, 2012; Lawrence *et al*., submitted-b).

Table 25-2 lists key constraints and corresponding enabling factors for effective institutional adaptation processes identified in Australia and New Zealand. Scientific uncertainty and resources limitations are reported consistently as important constraints, particularly for smaller councils. Ultimately more powerful constraints arise, however, from current legislative, institutional and governance arrangements and the lack of consistent tools to deal with dynamic risks and uncertainty or to evaluate the success of adaptation responses (*high agreement, robust evidence*; Britton, 2010; Mukheibir *et al*., 2013; Lawrence *et al*., submitted-b; Webb *et al*., submitted; see also Chapter 16).

[INSERT TABLE 25-2 HERE
Table 25-2: Constraints and enabling factors for institutional adaptation processes in Australasia.]

Some constraints exacerbate others. There is *high confidence* that the absence of a consistent information base and binding guidelines that clarify governing principles and liabilities is a challenge particularly for small and resource-limited local authorities, which need to balance special interest advocacy with longer term community resilience. This heightens reliance on individual leadership subject to short-term political change (Smith *et al*., 2008; Brown *et al*., 2009; Norman, 2009; Britton, 2010; Preston and Kay, 2010; Rouse and Norton, 2010; Smith *et al*., 2010; Abel *et al*., 2011; McDonald, 2011; Rive and Weeks, 2011; Corkhill, 2013). In these situations, planners tend to rely more on single numbers for climate change projections that can be argued in court (Reisinger *et al*., 2011; Lawrence *et al*., submitted-b), which increases the risk of maladaptation given the uncertain and dynamic nature of climate risk (McDonald, 2010; Stafford-Smith *et al*., 2011b; Gorrdard *et al*., 2012; McDonald, 2013; Reisinger *et al*., 2013).

Vulnerability assessments that take mid- to late-century impacts as their starting point can inhibit actors from implementing adaptation actions, as distant impacts are easily discounted and difficult to prioritise in competition with near-term non-climate change pressures (Productivity Commission, 2012). Emerging leading practice models in Australia (Balston, 2012; HCCREMS, 2012; SGS, 2012a, b) and New Zealand (MfE, 2008e; Britton *et al*., 2011) recommend a high-level scan of sectors and locations at risk and emphasise a focus on near-term decisions that influence current and future vulnerability (which could range from early warning systems to strategic and planning responses). More detailed assessment can then focus on this more tractable subset of issues, based on explicit and iterative framing of the adaptation issue (Webb *et al*., submitted) and taking into account the full lifetime (lead- and consequence time) of the decision/asset in question (Stafford-Smith *et al*., 2011b).

Participatory processes help balance societal preferences with robust scientific information and ensure ownership by affected communities (*high confidence*), but rely on human capital and political commitment (Hobson and Niemeyer, 2011; Rouse and Blackett, 2011; Weber *et al*., 2011; Leitch and Robinson, 2012). Realising widespread and equitable participation is challenging where policies are complex, debates polarised, legitimacy of institutions contested and potential transformational changes threaten deeply held values (Gardner *et al*., 2009a; Gorrdard *et al*., 2012; Burton and Mustelin, 2013; see also 25.4.3). Regional approaches that engage diverse stakeholders, government and science providers and support the co-production of knowledge can help overcome some of these problems but require long-term institutional and financial commitments (e.g. Britton *et al*., 2011; DSEWPC, 2011; CSIRO, 2012; IOCI, 2012; Low Choy *et al*., 2012; Webb and Beh, 2013).

An emerging literature questions whether incremental adjustments of existing planning instruments, institutions and decision-making processes can deal adequately with the dynamic and uncertain nature of climate change and support transformative responses (Kennedy *et al*., 2010; Preston *et al*., 2011; Park *et al*., 2012; McDonald, 2013; Stafford-Smith, 2013; Lawrence *et al*., submitted-b). Recent studies suggest a greater focus on flexibility and matching decision-making frameworks to specific problems (Hertzler, 2007; Nelson *et al*., 2008; Dobes, 2010; Howden and Stokes, 2010; Randall *et al*., 2012). Limitations of mainstreamed and autonomous adaptation (Dovers and Hezri, 2010) and the potential need for more proactive government intervention are being explored in Australia (see Productivity Commission, 2012, including submissions), but have not yet resulted in new policy frameworks.

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Box 25-1. Coastal Adaptation – Planning and Legal Dimensions

Sea level rise is a significant risk to Australia and New Zealand (*very high confidence*) due to intensifying coastal development and the location of population centres and infrastructure (Freeman and Cheyne, 2008; DCC, 2009; see also 25.3). Local case studies in New Zealand (Fitzharris, 2010; Reisinger *et al*., 2013) and national reviews in Australia (DCC, 2009; DCCEE, 2011) demonstrate risks to large numbers of residential and commercial assets as well as key services. In Australia, sea level rise of 1.1 m would affect over A$226 billion of assets, including up to 274,000 residential and 8,600 commercial buildings (DCCEE, 2011), with additional intangible costs related to stress, health effects and service disruption (HCCREMS, 2010). Under expected future settlement patterns, exposure of the Australian road and rail network will increase significantly once sea level rise exceeds about 0.5 m (Baynes *et al*., 2012). While the magnitude of sea level rise during the 21st century remains uncertain, its persistence over many centuries implies that realization of these risks is only a question of time (AR5 WGI Chapter 13).

Responsibility for adapting to sea level rise in Australasia rests principally with local governments through spatial planning instruments. Western Australia, South Australia and Victoria have mandatory State planning benchmarks for 2100, with local governments determining how they should be implemented. Long-term benchmarks in NSW and Queensland have either been suspended or revoked, so local authorities now have broad discretion to develop their own adaptation plans. The New Zealand Coastal Policy Statement (Minister of Conservation, 2010) mandates a minimum 100-year planning horizon for assessing hazard risks, discourages protection of existing development and recommends avoidance of new development in vulnerable areas. Non-binding government guidance recommends a risk based approach, using a base value of 0.5 m sea level rise by the 2090s and at least considering implications of greater rises of 0.8 m, and 0.1 m per decade beyond 2100, where relevant (MfE, 2008c).

The incorporation of climate change impacts into local planning has evolved considerably over the past 20 years, but remains piecemeal and shows a diversity of approaches (Gibbs and Hill, 2012; Kay *et al*., 2013). Many local governments lack the resources for hazard mapping and policy design. Political commitment is variable, and legitimacy of approaches and institutions is often strongly contested (Gorrdard *et al*., 2012), including pressure on State governments to modify adaptation policies and on local authorities to compensate developers for restrictions on current or future land uses (LGNZ, 2008; Berry and Vella, 2010; McDonald, 2010; Reisinger *et al*., 2011). There is *limited evidence* but *high agreement* that incremental local coastal adaptation responses can generate a path-dependency that becomes increasingly difficult to overcome (Gorrdard *et al*., 2012; McDonald, 2013), with appreciating land values supporting ever greater emphasis on protection (Fletcher *et al*., submitted). Strategic regional-scale planning initiatives in rapidly growing regions, like southeast Queensland, allow climate change adaptation to be addressed in ways that are not typically achieved by locality- or sector-specific plans, but require effective coordination across different scales of governance (Low Choy *et al*., 2013; Smith *et al*., 2013).

Courts in both countries have played an important role in evaluating planning measures. Results of litigation have varied and, in the absence of clearer legislative guidance, more litigation is expected as rising sea levels affect existing properties and adaptation responses constrain development on coastal land (MfE, 2008c; Rive and Weeks, 2011; Verschuuren and McDonald, 2012; Corkhill, 2013).

In addition to raising minimum floor levels and creating coastal set-backs to limit further development in areas at risk, several councils have attempted to implement managed retreat policies, such as Byron Shire Council, Australia (BSC, 2010), Environment Canterbury and Kapiti Coast District Council, New Zealand (ECAN, 2005; KCDC, 2012). These policies remain largely untested in New Zealand, but experience in Australia has shown high litigation potential and opposing priorities at different levels of government, undermining retreat policies (Parliament of Australia, 2009; DCC, 2010; Abel *et al*., 2011). Mandatory disclosure of information about future risks, community engagement and policy stability are critical to support retreat, but existing-use rights, liability concerns, special interests, community resources, place attachment and divergent priorities at different levels of government present powerful barriers (*high agreement, robust evidence*; Hayward, 2008a; Berry and Vella, 2010; McDonald, 2010; Abel *et al*., 2011; Alexander *et al*., 2012; Leitch and Robinson, 2012; Reisinger *et al*., 2013).

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25.4.3. Socio-cultural Factors Influencing Impacts of and Adaptation to Climate Change

Adapting to climate change relies on individuals accepting and understanding changing risks, implications, and opportunities, and responding to these risks and changes both psychologically and behaviourally within their respective spheres of influence (see Chapters 2, 16). The majority of Australasians accept the reality of climate change and less than 10% fundamentally deny its existence (high confidence; ShapeNZ, 2009; Leviston *et al*., 2011; Lewandowsky, 2011; Lewandowsky *et al*., 2012; Milfont, 2012; Reser *et al*., 2012b, c). Australians generally perceive themselves to be at higher risk from climate change than New Zealanders and citizens of many other countries, which may reflect recent climatic extremes and their impacts (Gifford *et al*., 2009; Agho *et al*., 2010; Ashworth *et al*., 2011; Milfont *et al*., 2012; Reser *et al*., 2012b). However, beliefs about climate change and the risks posed vary over time, are uneven across society and reflect media coverage and bias, political preferences, and gender (ShapeNZ, 2009; Bacon, 2011; Leviston *et al*., 2012; Milfont, 2012), which can influence the willingness of

communities and businesses to consider adaptation (Gardner *et al*., 2010; Gifford, 2011; Reser *et al*., 2011; Alexander *et al*., 2012; Raymond and Spoehr, 2013).

Surveys in Australia between 2007 and 2011 show moderate to high levels of climate change concern, distress, frustration, resolve, motivation, psychological adaptation, and carbon-reducing behavioural engagement (high agreement, medium evidence; Agho *et al*., 2010; Reser *et al*., 2012b, c). About two thirds of respondents perceived global warming as likely to worsen, with about half very or extremely concerned that they or their family would be directly affected. Direct personal experience with environmental changes or events attributed to climate change, reported by 45% of respondents, was particularly significant and influential, but concern about global warming was also linked to general psychological distress levels. The extent to which distress and concern about climate change impacts translate into actual support for proactive adaptation responses has not yet been fully assessed.

Perceived levels of risk and potential losses from climate change depend on values attributed and invested by individuals to specific places, activities and objects. Examples from Australia include the value placed on winter snow cover in the Snowy Mountains (Gorman-Murray, 2008, 2010), risks to biodiversity and recreational values in coastal South Australia (Raymond and Brown, 2011), conflicts between human uses and environmental priorities in national parks (Wyborn, 2009; Roman *et al*., 2010), and alternative uses of limited water resources in rural areas (Alston, 2010; Hurlimann and Dolnicar, 2011; Kingsford *et al*., 2011). These and additional studies in Australasia addressing place connection and environmental change (e.g. Rogan *et al*., 2005; McCleave *et al*., 2006; Collins and Kearns, 2010; Gosling and Williams, 2010; Raymond *et al*., 2011) confirm the importance of place attachment in understanding psychological dimensions of climate change impacts.

Acceptable adaptation responses are similarly influenced and often constrained by social and cultural values and norms. Place attachment and differing values relating to near- versus long-term, private versus public costs and benefits, and legitimacy of institutions influence adaptation preferences, e.g. in the coastal zone (Hayward, 2008b; Agyeman *et al*., 2009; King *et al*., 2010; Gorrdard *et al*., 2012; Hofmeester *et al*., 2012) and acceptance of water recycling or pricing (Pearce *et al*., 2007; Miller and Buys, 2008; Hurlimann and Dolnicar, 2010; Kouvelis *et al*., 2010; Mankad and Tapsuwan, 2011). On the other hand, place attachment, connection, and identity can also offer substantial benefits and support with respect to adaptation challenges and impacts, including stress reduction, restoration, recreation, and continuity, and enhancement of environmental quality, subjective well being, and mental health, especially for disadvantaged and indigenous communities (Berry *et al*., 2010; see also 25.9.2).

These studies indicate that the threat of and direct and indirect experience of climate change and extreme climatic events are having appreciable psychological impacts, but also result in psychological and subsequent behavioural adaptations, reflected in high levels of acceptance and realistic concern, motivational resolve, self-reported changes in thinking, feeling and understanding of climate change and its implications, and behavioural engagement (Reser and Swim, 2011; Reser *et al*., 2012a; Reser *et al*., 2012b, c). However, adequate ongoing and standardised impact assessment strategies and systems are lacking to monitor trends and to compare impacts with bio-physical and economic impacts that dominate the climate change vulnerability literature.

25.5. Freshwater Resources

25.5.1. Projected Impacts

Impact of climate change on water resources and river flow characteristics is a cross-cutting issue affecting people, agriculture, industries and ecosystems. The challenge of satisfying multiple demands with a limited resource is exacerbated by the high inter-annual and inter-decadal variability of river flows (Chiew and McMahon, 2002; Peel *et al*., 2004; Verdon *et al*., 2004; McKerchar *et al*., 2010) particularly in Australia.

Figure 25-4 shows estimated changes to mean annual runoff across Australia for a 1°C global average warming (Chiew and Prosser, 2011; Teng *et al*., 2012). The range of estimates arises mainly from uncertainty in projected precipitation (Table 25-1). Hydrological modelling based on CMIP3 climate models indicates that freshwater resources in far south-eastern and far south-west Australia will decline (*high confidence;* by 0-40% and 20-70%,

respectively, for 2°C warming) due to the reduction in winter half-year precipitation (Table 25-1 and Figure 25-3) when most of the runoff in southern Australia occurs. The percent change in mean annual precipitation in Australia is generally amplified as a 2–3 times larger percent change in mean annual streamflow (Chiew, 2006; Jones *et al.*, 2006). This can vary, however, with unprecedented declines in flow in far south-eastern Australia in the 1997–2009 drought (Cai and Cowan, 2008; Potter *et al.*, 2010; Chiew *et al.*, 2011; Potter and Chiew, 2011). Higher temperatures and associated evaporation, tree re-growth following more frequent bushfires (Kuczera, 1987; Cornish and Vertessy, 2001; Marcar *et al.*, 2006; Lucas *et al.*, 2007), interception activities like farm dams (Van Dijk *et al.*, 2006; Lett *et al.*, 2009) and reduced surface-groundwater connectivity in long dry spells (Petrone *et al.*, 2010; Hughes *et al.*, 2012) can further accentuate declines. In the longer-term, water availability will also be affected by changes in vegetation and surface-atmosphere feedbacks from a warmer and higher CO_2 environment (Betts *et al.*, 2007; Donohue *et al.*, 2009; McVicar *et al.*, 2010).

[INSERT FIGURE 25-4 HERE
Figure 25-4: Estimated changes in mean annual runoff for a 1°C global average warming. Maps show changes in annual runoff (percentage change; top row) and runoff depth (millimetres; bottom row), for median, dry and wet (10^{th} and 90^{th} percentile) range of estimates, based on hydrological modelling using CMIP3 models (Chiew *et al.*, 2009; CSIRO, 2009b; Petheram *et al.*, 2012; Post *et al.*, 2012). Projections for 2°C global average warming are about twice that shown in the maps (Post *et al.*, 2011). (Figure adapted from Chiew and Prosser, 2011; Teng *et al.*, 2012).]

In New Zealand, projected precipitation changes (Table 25-1) will generally lead to increased runoff in the west and south of the South Island and reduced runoff in the north-east of the South Island, and the east and north of the North Island (*medium confidence*). Annual flows of eastward flowing rivers with headwaters in the Southern Alps (Clutha, Waimakariri, Rangitata) are projected to increase by 5-10 % (median projection) by 2040 (Bright *et al.*, 2008; Poyck *et al.*, 2011; Zammit and Woods, 2011b, a) in response to higher alpine precipitation. Most of the projected increases occur in winter and spring, as more precipitation falls as rain and snow melts earlier. In contrast, the Ashley River, slightly north of this region, is projected to have little change in annual flows, with the increase in winter flows offset by reduced summer flows (Woods *et al.*, 2008). The retreat of glaciers is expected to have only a minor impact on river flows in the first half of the century (Chinn, 2001; Anderson *et al.*, 2008). Limited modelling studies show reduced mean annual streamflow in the east and north of the North Island: for example by 14% (median projection) by 2040 in the Waipaoa River, in response to projected precipitation decline and higher temperature (Zemansky, 2010; Collins, 2012).

Climate change will affect groundwater through changes in recharge rates and the relationship between surface waters and aquifers. Dryland diffuse recharge in most of western, central and southern Australia is projected to decrease because of the decline in precipitation, with increases in the north and some parts of the east because of projected increase in extreme rainfall intensity (*medium confidence*; Crosbie *et al.*, 2010; McCallum *et al.*, 2010; Crosbie *et al.*, 2012). There has been little research in New Zealand, with one study projecting groundwater recharge in the Canterbury Plains to decrease by about 10% by 2040 (Bright *et al.*, 2008).

25.5.2. Adaptation

The 1997-2009 ‘Millennium’ drought in south-eastern Australia and projected declines in future water resources in southern Australia are already stimulating adaptation (Box 25-2). In New Zealand, there is little evidence of this. Water in New Zealand is not as scarce generally and water policy reform is driven more by pressure to maintain water quality while expanding agricultural activities, with an increasing focus on collaborative management (Memon and Skelton, 2007; Memon *et al.*, 2010; Lennox *et al.*, 2011; Weber *et al.*, 2011) within national guidelines (LWF, 2010; MfE, 2011). Impacts of climate change on water supply, demand and infrastructure have been considered by several local authorities and consultancy reports (Jollands *et al.*, 2007; Williams *et al.*, 2008; Kouvelis *et al.*, 2010), but no explicit management changes have yet resulted.

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Box 25-2. Adaptation through Water Resources Policy and Management in Australia

Water policy and management in Australia is focused on allocating an often scarce resource exhibiting high seasonal, annual and decadal variability (Chiew and Prosser, 2011; Prosser, 2011). Widespread drought and projections of a drier future in south-eastern and far south-west Australia (Bates *et al*., 2010; CSIRO, 2010; Potter *et al*., 2010; Chiew *et al*., 2011) saw extensive policy and management change in both rural and urban water systems (Hussey and Dovers, 2007; Bates *et al*., 2008; Melbourne Water, 2010; DSE, 2011; MDBA, 2011; NWC, 2011; Schofield, 2011). These management changes provide examples of adaptations, building on previous policy reforms dealing with climate variability but less explicitly with climate change (Botterill and Dovers, 2013).

The broad policy framework is set out in the 2004-2014 National Water Initiative and the 2007 Commonwealth Water Act. The establishment of the National Water Commission (2004) and the Murray-Darling Basin Authority (2008) were major institutional reforms. The National Water Initiative explicitly recognises climate change as a constraint on future water allocations. Official assessments (NWC, 2009, 2011) and critiques (Connell, 2007; Grafton and Hussey, 2007; Byron, 2011; Crase, 2011; Pittock and Finlayson, 2011) have discussed progress and shortcomings of the initiative, but assessment of its overall success is made difficult by other factors such as on-going revisions to allocation plans and time lags to observable impacts.

Rural water reform in south-eastern Australia, focused on the Murray-Darling Basin, is still unfolding. The first draft Murray-Darling Basin Plan (MDBA, 2011) aims to return 2750 GL/year of consumptive water (about one fifth of current entitlements) to riverine ecosystems and develop flexible and adaptive water sharing plans to cope with current and future climates, although climate change is not factored in explicitly. The Plan recommends more than A$10 billion be spent on public buyback of entitlements, upgrading infrastructure, and improving water use efficiency. Water markets are a key policy instrument, allowing water use patterns to adapt to shifting availability and move toward higher value water (NWC, 2010; Kirby *et al*., 2012). For example, the two-thirds reduction in irrigation water use over the 1997-2009 drought in the Basin resulted in only 20% reduction in agricultural returns, mainly because water use shifted to more valuable enterprises (Kirby *et al*., 2012). Elsewhere, catchment management authorities and state agencies throughout south-eastern Australia develop water management strategies to cope with prolonged droughts and climate change (e.g. DSE, 2011). Nevertheless, if the extreme dry end of future water projections is realized (25.5.1, Figure 25-4), agriculture and ecosystems across south-eastern Australia would be threatened even with comprehensive adaptation (see 25.6.2, 25.7.2; Connor *et al*., 2009; Kirby *et al*., in press).

Many capital cities in Australia are reducing their reliance on catchment runoff and groundwater as these sources are most sensitive to climate change and drought, and are diversifying supplies by investing in desalinisation plants, water re-use and integrated water cycle management. Concurrently, demand is being reduced through water conservation and water sensitive urban design and, during severe shortfalls, through implementation of restrictions. In Melbourne, for example, planning has centred on securing new supplies that are more resilient to major climate shocks, increasing use of alternative sources like sewage recycling and stormwater for non-potable water, programs to reduce demand, and integrated planning that also considers integration with climate change impacts on flood risk and on urban stormwater and wastewater infrastructures (DSE, 2007; Skinner, 2010; DSE, 2011; Rhodes *et al*., 2012). Melbourne's water augmentation program includes a desalinisation plant with a 150 GL/year capacity (about one third of the current demand), following the lead of Perth in far south-west Australia where a desalinisation plant was established in 2006 following declining inflows since the mid-1970s (Hennessy *et al*., 2007; Bates and Hughes, 2009). Melbourne's water conservation strategies include water efficiency and rebate programs for business and industry, water smart gardens, dual flush toilets, grey water systems, rainwater tank rebates, free water-efficient showerheads and voluntary residential use targets. These conservation measures, together with water restrictions since the early 2000s, have reduced Melbourne's total per capita use by 40% (Fitzgerald, 2009; Rhodes *et al*., 2012). Similar recent programs reduced Brisbane's per capita use by about 50% (Shearer, 2011), while adoption of water recycling and rainwater harvesting resulted in up to 60% water savings in some parts of Adelaide (Barton and Argue, 2009; Radcliffe, 2010).

The success of urban water reforms in the face of drought and climate change can be interpreted in different ways. Increasing supply through desalinisation plants and water reuse schemes reduces the risk of future water shortages and helps cities cope with increasing population. Uptake of household-scale adaptation options has been significant in some locations, but their long-term sustainability or reversibility in response to changing drivers and societal attitudes is an open question (Troy, 2008; Brown and Farrelly, 2009; Mankad and Tapsuwan, 2011). In addition, desalinisation plants can be maladaptive in that they are energy intensive, and the enhancement of traditional mass supply could create a disincentive for reducing demand or increasing resilience by diversifying supply (Barnett and O'Neill, 2010; Taptiklis, 2011).

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25.6. Natural Ecosystems

25.6.1. Terrestrial and Inland Freshwater Ecosystems

Terrestrial and freshwater ecosystems have suffered high rates of habitat loss and degradation, and species extinctions since European settlement (Kingsford *et al.*, 2009; Bradshaw *et al.*, 2010; McGlone *et al.*, 2010; Lundquist *et al.*, 2011; SoE, 2011); many reserves are small and isolated, and some key ecosystems and species under-represented (Walker *et al.*, 2006; Sattler and Taylor, 2008; MfE, 2010b; SoE, 2011). Freshwater ecosystems in both countries are pressured from over-allocation, agriculture and pollution (e.g. Ling, 2010). Additional stresses include erosion, changes in nutrients and fire regimes, mining, invasive species, grazing and salinity (Kingsford *et al.*, 2009; McGlone *et al.*, 2010; SoE, 2011). These increase vulnerability to rapid climate change and provide challenges for both autonomous and managed adaptation (Burbidge *et al.*, 2008).

25.6.1.1. Observed Impacts

In Australian terrestrial systems, some recently observed changes in the distributions, genetics and phenology of individual species, and in the structure and composition of some ecological communities can be attributed to recent climatic and atmospheric trends (*medium* to *high confidence*; see Box 25-3). Uncertainty remains regarding the role of non-climatic drivers, including changes in fire management, grazing and land-use. The 1997-2009 drought had severe impacts in freshwater systems in the eastern States and the Murray Darling Basin (Pittock and Finlayson, 2011) but in many freshwater systems, direct climate impacts are difficult to detect above the strong signal of over-allocation, pollution, sedimentation, exotic invasions and natural climate variability (Jenkins *et al.*, 2011). In New Zealand, few if any impacts have been directly attributed to climate change rather than variability (Box 25-3; McGlone *et al.*, 2010; McGlone and Walker, 2011). Alpine treelines in New Zealand have remained roughly stable for several hundred years (*high confidence*) despite 0.9°C average warming (McGlone *et al.*, 2010; McGlone and Walker, 2011; Harsch *et al.*, 2012).

25.6.1.2. Projected Impacts

Existing environmental stresses will interact with, and in many cases be exacerbated by, shifts in mean climatic conditions and associated increase in the frequency or intensity of extreme events, especially fire, drought and floods (*high confidence*; Steffen *et al.*, 2009; Bradstock, 2010; Murphy *et al.*, 2012). Recent drought-related mortality of amphibians in south-east Australia (Mac Nally *et al.*, 2009); savannah trees in north-east Australia (Fensham *et al.*, 2009; Allen *et al.*, 2010); eucalypts in sub-alpine regions in Tasmania (Calder and Kirkpatrick, 2008); and mass die-offs of flying foxes and cockatoos during heatwaves (Welbergen *et al.*, 2008; Saunders *et al.*, 2011) provide *high confidence* that extreme heat combined with reduced water availability will be a significant driver of future population loss and increase the risk of local species extinctions (e.g. McKechnie and Wolf, 2010; see also Figure 25-5).

Species distribution modelling (SDM) consistently indicates future range contractions for Australia's native species even assuming optimistic rates of dispersal, e.g. WA *Banksia* spp. (Fitzpatrick *et al*., 2008), koalas (Adams-Hosking *et al*., 2011), northern macropods (Ritchie and Bolitho, 2008), native rats (Green *et al*., 2008b), greater gliders (Kearney *et al*., 2010b), quokkas (Gibson *et al*., 2010), platypus (Klamt *et al*., 2011) and fish (Bond *et al*., 2011). In some studies, complete loss of climatically suitable habitat is projected for some species within a few decades, and therefore increased risk of local and, perhaps, global extinction (*medium confidence*). SDM has limitations (e.g. Elith *et al*., 2010; McGlone and Walker, 2011) but is being improved through integration with physiological (Kearney *et al*., 2010b) and demographic models (Keith *et al*., 2008; Harris *et al*., 2012), and incorporation into broader risk assessments (e.g. Williams *et al*., 2008; Crossman *et al*., 2012).

In Australia, assessments of ecosystem vulnerability have been based on observed changes, coupled with projections of future climate in relation to known biological thresholds and assumptions about adaptive capacity (e.g. Laurance *et al*., 2011; Murphy *et al*., 2012). There is *very high confidence* that one of the most vulnerable Australian ecosystems is the alpine zone, from loss of snow cover, with flow on impacts such as exotic species invasions and changed species interactions (Pickering *et al*., 2008). There is also *high confidence* in substantial risks to coastal wetlands such as Kakadu National Park subject to saline intrusion (BMT WBM, 2011); tropical savannas subject to changed fire regimes (Laurance *et al*., 2011); inland freshwater and groundwater systems subject to drought, over-allocation and altered timing of floods (Lake and Bond, 2007; Pittock, 2008; Pittock *et al*., 2008; Nielsen and Brock, 2009; Balcombe *et al*., 2011; Jenkins *et al*., 2011; Morrongiello *et al*., 2011; Pratchett *et al*., 2011; Kroon *et al*., 2012); peat-forming wetlands along the east coast (Keith *et al*., 2010); and biodiversity-rich regions such as southwest Western Australia (Yates *et al*., 2010a; Yates *et al*., 2010b) and rainforests in Queensland (Stork *et al*., 2007; Shoo *et al*., 2011; Murphy *et al*., 2012).

The very few studies of climate change impacts on biodiversity in New Zealand suggest that on-going impacts of invasive species (Box 25-4) and habitat loss will dominate climate change signals in the short- to medium-term (McGlone *et al*., 2010), but that atmospheric and climatic change have the potential to exacerbate existing stresses (McGlone and Walker, 2011). There is *limited evidence but high agreement* that the rich biota of the alpine zone is at risk through increasing shrubby growth and loss of herbs, especially if combined with increased establishment of invasive species (McGlone *et al*., 2010; McGlone and Walker, 2011). Some cold water-adapted freshwater fish and invertebrates are vulnerable to warming (August and Hicks, 2008; Winterbourn *et al*., 2008; Hitchings, 2009; McGlone and Walker, 2011) and increased spring flooding may increase risks for braided-river bird species (MfE, 2008d). For some restricted native species, suitable habitat may increase with warming (e.g. native frogs; Fouquet *et al*., 2010) although limited dispersal ability will limit range expansion. Tuatara populations are at risk as warming increases the ratio of males to females (Mitchell *et al*., 2010), although the lineage has persisted during higher temperatures in the geological past (McGlone and Walker, 2011).

25.6.1.3. Adaptation

High levels of endemism in both countries (Lindenmayer, 2007; Lundquist *et al*., 2011) are associated with narrow geographic ranges and associated climatic vulnerability, although there is greater scope for adaptive dispersal to higher elevations in New Zealand than in Australia. Anticipated rates of climate change, together with fragmentation of remaining habitat and limited migration options in many regions (Steffen *et al*., 2009; Morrongiello *et al*., 2011), will limit *in situ* adaptive capacity and distributional shifts to more climatically suitable areas for many species (*high confidence*). Significant local and global losses of species and ecosystem services, and large scale changes in ecological communities, are anticipated (e.g. Dunlop *et al*., 2012; Murphy *et al*., 2012).

There is increasing recognition in Australia that rapid climate change has fundamental implications for traditional conservation objectives (e.g. Steffen *et al*., 2009; Prober and Dunlop, 2011; Dunlop *et al*., 2012; Murphy *et al*., 2012). Research on impacts and adaptation in terrestrial and freshwater systems has been guided by the National Adaptation Research Plans (Hughes *et al*., 2010; Bates *et al*., 2011). Climate change adaptation plans developed by many levels of government and Natural Resource Management (NRM) bodies, supported by substantial federal government funding, have identified priorities that include: identification and protection of climatic refugia (Shoo *et al*., 2011); restoration of riparian zones to reduce stream temperatures (Davies, 2010; Jenkins *et al*., 2011);

construction of levees to protect wetlands from saltwater intrusion (Jenkins *et al*., 2011); reduction of non-climatic threats such as invasive species to increase ecosystem resilience (Kingsford *et al*., 2009); ecologically-appropriate fire regimes (Driscoll *et al*., 2010); restoration of environmental flows in major rivers (Kingsford and Watson, 2011; Pittock and Finlayson, 2011); protecting and restoring habitat connectivity in association with expansion of the protected area network (Dunlop and Brown, 2008; Mackey *et al*., 2008; Taylor and Philp, 2010; Prowse and Brook, 2011); and active interventionist strategies such as assisted colonisation (Burbidge *et al*., 2011; McIntyre, 2011). The effectiveness of these measures cannot yet be assessed. Biodiversity research and management in New Zealand to date has taken little account of climate change-related pressures and continues to focus largely on managing pressures from invasive species and predators, freshwater pollution, exotic diseases, and halting the decline in native vegetation, although a number of specific recommendations have been made to improve ecosystem resilience to future climate threats (McGlone *et al*., 2010; McGlone and Walker, 2011).

Climate change responses in other sectors may have beneficial as well as adverse impacts on biodiversity, but few tools to assess risks from an integrated perspective have been developed (25.9.1, Box 25.10).

25.6.2. Coastal and Ocean Ecosystems

Australia's 60,000 km coastline spans tropical waters in the north to cool temperate waters off Tasmania and the sub-Antarctic islands with sovereign rights over ~8.1 million km^2, excluding the Australian Antarctic Territory (Richardson and Poloczanska, 2009). New Zealand has ~18,000 km of coastline, spanning subtropical to sub-Antarctic waters, and the world's fifth largest Exclusive Economic Zone at 4.2 million km^2 (Gordon *et al*., 2010). The marine ecosystems of both are considered hotspots of global marine biodiversity with many rare, endemic and commercially important species (Hoegh-Guldberg *et al*., 2007; Blanchette *et al*., 2009; Gordon *et al*., 2010; Gillanders *et al*., 2011; Lundquist *et al*., 2011). The increasing density of coastal populations (25.3) and stressors such as pollution and sedimentation from settlements and agriculture will intensify non-climate stressors in coastal areas (*high confidence*; e.g. Russell *et al*., 2009). Coastal habitats also store carbon, particularly seagrass, saltmarsh and mangroves, which could become increasingly important for mitigation (e.g. Irving *et al*., 2011). Coastal ecosystems occupy <1% of the land mass but may account for 39% of Australia's average national annual carbon burial (estimated total: 466 millions tonnes CO_2-eq per year; Lawrence *et al*., 2012).

25.6.2.1. Observed Impacts

There is *high confidence* that climate change is already affecting the oceans around Australia (Pearce and Feng, 2007; Poloczanska *et al*., 2007; Lough and Hobday, 2011) and warming the Tasman sea in northern New Zealand (Sutton *et al*., 2005; Lundquist *et al*., 2011); average climate zones have shifted south by more than 200 km along the northeast and about 100 km along the northwest Australian coasts (Lough, 2008). The rate of warming is even faster in southeast Australia, with a poleward advance of the East Australia Current of ~350 km over the past 60 years (Ridgway, 2007; Wu *et al*., 2012). Based on elevated rates of ocean warming, southwest and southeast Australia are recognized as global warming hotspots (Wernberg *et al*., 2011; Wu *et al*., 2012).

Observed impacts on marine species around Australia have been reported from a range of trophic levels (Box 25-3) and include changes in phytoplankton productivity (Thompson *et al*., 2009; Johnson *et al*., 2011); species abundance of macroalgae (Johnson *et al*., 2011); growth rates of abalone (Johnson *et al*., 2011), southern rock lobster (Pecl *et al*., 2009; Johnson *et al*., 2011), coastal fish (Neuheimer *et al*., 2011) and coral (De'ath *et al*., 2009); life cycles of southern rock lobster (Pecl *et al*., 2009) and seabirds (Cullen *et al*., 2009; Chambers *et al*., 2011); and distribution of subtidal seaweeds (Johnson *et al*., 2011; Wernberg *et al*., 2011; Smale and Wernberg, 2013), plankton (McLeod *et al*., 2012), fish (Figueira *et al*., 2009; Figueira and Booth, 2010; Last *et al*., 2011; Madin *et al*., 2012), sea urchins (Ling *et al*., 2009) and intertidal invertebrates (Pitt *et al*., 2010).

Habitat-related impacts are more prevalent in northern Australia (Pratchett *et al*., 2011), while distribution changes are reported more often in southern waters (Madin *et al*., 2012), particularly south-east Australia, where warming has been greatest. The 2011 marine heat wave in Western Australia caused the first-ever reported bleaching at

Ningaloo reef, as well as reports of southern range extensions of many marine species, and declines in local abundance (Wernberg *et al*., 2013). About 10% of the observed 50% decline in coral cover on the Great Barrier Reef has been attributed to bleaching, the remainder to cyclones and predators (De'ath *et al*., 2012). Changes in distribution and abundance of marine species in New Zealand are primarily linked to ENSO-related variability that dominates in many time series (Clucas, 2011; Lundquist *et al*., 2011; McGlone and Walker, 2011; Schiel, 2011), although water temperature is also important (e.g. Beentjes and Renwick, 2001). New Zealand fisheries export some $1.4 billion worth of product and variability in ocean circulation and temperature plays an important role in local fish abundance (e.g. Chiswell and Booth, 2005; Dunn *et al*., 2009), but no climate change impacts have been reported at this stage (Dunn *et al*., 2009).

25.6.2.2. Projected Impacts

Even though evidence to date of climate impacts on coastal habitats is limited, *confidence* is *high* that negative impacts will arise with continued climate change (Lovelock *et al*., 2009; McGlone and Walker, 2011; Traill *et al*., 2011). Some coastal habitats such as mangroves are projected to expand further landward, driven by sea-level rise and exacerbated by soil subsidence if rainfall declines (*medium confidence*; Traill *et al*., 2011), although this may be at the expense of saltmarsh and constrained in many regions by the built environment (DCC, 2009; Lovelock *et al*., 2009; Rogers *et al*., 2012). Estuarine habitats will be affected by changing rainfall or sediment discharges, as well as connectivity to the ocean (*high confidence*; Gillanders *et al*., 2011). Loss of coastal habitats and declines in iconic species will result in substantial impacts on coastal settlements and infrastructure from direct impacts such as storm surge, and tourism (*medium confidence*; 25.7.5).

Change in temperature and rainfall, and sea level rise, are expected to lead to secondary effects, including erosion, landslips, and flooding, affecting coastal habitats and their dependent species, e.g. loss of habitat for nesting birds (*high confidence*; Chambers *et al*., 2011). Increasing ocean acidification is expected to affect many taxa (*medium confidence*; see also Box CC-OA) including corals (Fabricius *et al*., 2011), coralline algae (Anthony *et al*., 2008), calcareous plankton (Richardson *et al*., 2009; Thompson *et al*., 2009; Hallegraeff, 2010), reef fishes (Munday *et al*., 2009; Nilsson *et al*., 2012), bryozoans and other benthic calcifiers (Fabricius *et al*., 2011). Deep-sea scleractinian corals off New Zealand and Australia are also expected to decline with ocean acidification (Miller *et al*., 2011).

The AR4 identified the Great Barrier Reef (GBR) as highly vulnerable to warming and acidification (Hennessy *et al*., 2007). Recent observations of bleaching and reduced calcification in both the GBR and other reef systems (Cooper *et al*., 2008; De'ath *et al*., 2009; Cooper *et al*., 2012), along with model and experimental studies (Hoegh-Guldberg *et al*., 2007; Anthony *et al*., 2008; Veron *et al*., 2009) confirm this vulnerability (see also Box CC-CR). There is *high confidence* that the combined impacts of warming and acidification associated with atmospheric CO_2 concentrations in excess of 450-500 ppm will be associated with increased frequency and severity of coral bleaching, disease incidence and mortality, leading to dominance by macroalgae (Hoegh-Guldberg *et al*., 2007; Veron *et al*., 2009). Bleaching frequency is expected to increase and become decoupled from the 4-7 year El Niño cycle (Veron *et al*., 2009). Other stresses, including rising sea levels, increased cyclone intensity, and nutrient-enriched runoff, will exacerbate these impacts (*high confidence*; Hoegh-Guldberg *et al*., 2007; Veron *et al*., 2009). Thermal thresholds and the ability to recover from bleaching events vary geographically and between species (e.g. Diaz-Pulido *et al*., 2009) but evidence of the ability of corals to adapt to rising temperatures and acidification is limited and appears insufficient to offset the detrimental effects of warming and acidification (*robust evidence, medium agreement*; Hoegh-Guldberg et al., 2007; Veron et al., 2009).

Under all SRES scenarios and a range of CMIP3 models, pelagic fishes such as sharks, tuna and billfish are projected to move further south on the east and west coasts of Australia (*high confidence*; Hobday, 2010). These changes depend on sensitivity to water temperature, and may lead to shifts in species-overlap with implications for by-catch management (Hartog *et al*., 2011). Poleward movements are also projected for coastal fish species in Western Australia (Cheung *et al*., 2012). A strengthening East Auckland Current in northern New Zealand is expected to promote establishment of tropical or sub-tropical species that currently occur as vagrants in warm La Niña years (Willis *et al*., 2007). Such shifts suggest potentially substantial changes in production and profit of both wild fisheries (Norman-Lopez *et al*., 2011) and aquaculture species such as salmon, mussels and oysters (*medium*

confidence; Hobday *et al*., 2008; Hobday and Poloczanska, 2010). Ecosystem models also project changes to habitat and fisheries production (*low confidence*; Fulton, 2011; Watson *et al*., 2012).

25.6.2.3. Adaptation

In Australia, research on marine impacts and adaptation has been guided by the National Adaptation Research Plan for Marine Biodiversity and Resources (Mapstone *et al*., 2010). Planned adaptation options include removal of human barriers to landward migration of species, beach nourishment, management of environmental flows to maintain estuaries (Jenkins *et al*., 2010), habitat provision (Hobday and Poloczanska, 2010), translocation of seagrass and species such as turtles (e.g. Fuentes *et al*., 2009) and burrow modification for nesting seabirds (Chambers *et al*., 2011). For southern species on the continental shelf, options are more limited because suitable habitat will not be present – the next shallow water to the south is Macquarie Island. There is *low confidence* about the adequacy of autonomous rates of adaptation by species, although recent experiments with coral reef fish suggest that some species may adapt to the projected climate changes (Miller *et al*., 2012).

Management actions to increase coral reef resilience include reducing fishing pressure on herbivorous fish, protecting top predators, managing runoff quality, and minimizing other human disturbances, especially through marine protected areas (Hughes *et al*., 2007; Veron *et al*., 2009; Wooldridge *et al*., 2012). There is *high confidence* that such actions will slow, but not prevent, long-term degradation of reef systems once critical thresholds of ocean temperature and acidity are exceeded, and so novel options, including translocation and shading critical reefs, have been proposed (Rau *et al*., 2012). Forecasting can also prepare managers for bleaching events (Spillman, 2011).

Adaptation by the fishing industry to shifting distributions of target species is considered possible by most stakeholders (e.g. southern rock lobster fishery; Pecl *et al*., 2009). Translocation to maintain production in the face of declining recruitment may also be possible for some high value species, and has been trialled for the southern rock lobster (Green *et al*., 2010a). Options for aquaculture include disease management, alternative site selection, and selective breeding (Battaglene *et al*., 2008), although implementation is only in preliminary stages for both Australia and New Zealand. Marine protected area planning is not explicitly considering climate change in either country, but reserve performance will be affected by the projected environment shifts and novel combinations of species, habitats and human pressures (Hobday, 2011).

_____ START BOX 25-3 HERE _____

Box 25-3. Impacts of a Changing Climate in Natural and Managed Ecosystems

Observed changes in species, and in natural and managed ecosystems (25.6.1, 25.6.2, 25.7.2) provide multiple lines of evidence of the impacts of a changing climate[1]. Examples of observations published since the AR4 are shown in Table 25-3. At present only one study describes a climate-related change in a managed ecosystem (wine grape ripening in Australia; Webb *et al*., 2012a). It remains unclear whether this imbalance is due to confounding factors or a lack of published research.

[INSERT TABLE 25-3 HERE
Table 25-3: Examples of detected changes in species, natural and managed ecosystems, consistent with a climate change[1] signal, published since the AR4. Confidence in detection of change is based on the length of study, and the type, amount and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate as a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change.]

[FOOTNOTE 1: Consistent with the IPCC definition, a change in climate refers to any statistically detectable signal, it does not necessarily imply a human cause. See Glossary, Table 25-1 and 25.2.]

_____ END BOX 25-3 HERE _____

25.7. Major Industries

25.7.1. Production Forestry

Australia has about 149 Mha forests (includes woodlands, 2 Mha plantations, 9.4 Mha multiple-use native forests; MPIGA, 2008; Gavran and Parsons, 2010), and forestry contributes around $7 billion annually to GDP (ABARES, 2011a). New Zealand's plantation estate comprises about 1.7 Mha (90% *Pinus radiata*), with recent contractions due to increased profitability of dairying (MfE, 2008b; NZPFI, 2012).

25.7.1.1. Observed and Projected Impacts

Existing climate variability and other confounding factors have so far prevented the detection of climate change impacts on forests. Modelled projections are based on ecophysiological responses of forests to CO_2, water and temperatures. In Australia, potential changes in water availability will be most important (*very high confidence*). Modelling future distributions or growth rates indicate that plantations in south-west Western Australia are most at risk due to declining rainfall, and there is *high confidence* that plantation growth will be reduced by temperature increases in hotter regions, especially where species are grown at the upper range of their temperature tolerances (Medlyn *et al*., 2011a). There is *limited evidence* and *medium agreement* that moderate reductions in rainfall and increased temperature could be offset by fertilisation from increasing CO_2 (Simioni *et al*., 2009). In cool regions where water is not limiting, higher temperatures could benefit production (Battaglia *et al*., 2009). In New Zealand, temperatures are mostly sub-optimal for forest growth and water relations are generally less limiting (Kirschbaum and Watt, 2011). Warming is expected to increase *P. radiata* growth in the cooler south (*very high confidence*). In the warmer north, temperature increases can reduce productivity, but CO_2 fertilisation may offset this (*medium confidence*; Kirschbaum *et al*., 2012).

Modelling studies are limited by their reliance on key assumptions which are difficult to verify experimentally, e.g. either no or strong down-regulation of photosynthesis under elevated CO_2 (Battaglia *et al*., 2009). Most studies also exclude impacts of pests, diseases, weeds, fire and wind damage that may change adversely with climate. Fire, for instance, poses a significant threat in Australia and is expected to worsen with climate change (see Box 25.6), especially for the commercial forestry plantations in the southern winter-rainfall regions (Williams *et al*., 2009; Clarke *et al*., 2011). In New Zealand, changes in biotic factors are particularly important as they already affect plantation productivity. *Dothistroma* blight, for instance, is a serious pine disease with a temperature optimum that coincides with New Zealand's warmer, but not warmest, pine-growing regions (Watt *et al*., 2011a). Under climate change, its severity is, therefore, expected to reduce in the warm central North Island but increase in the cooler South Island (*high confidence*) where it could offset temperature-driven improved plantation growth. There is *medium evidence* and *high agreement* of similar future southward shifts in the distribution of existing plantation weed, insect pest and disease species in Australia (see review in Medlyn *et al*., 2011b).

25.7.1.2. Adaptation

Adaptation strategies include changes to species or provenance selection, and adopting different silvicultural options, e.g. fertilizer management or modified stand stocking (White *et al*., 2009; Booth *et al*., 2010). Depending on the extent of climate changes, and plant responses to increasing CO_2, the above studies (25.7.1.1) provide *limited evidence* but *high agreement* of potential net increased productivity in many areas, but only where soil nutrients are not limiting. The rotation time of plantation forests of about 30 years or more makes proactive adaptation important but also challenging. There is *medium evidence* and *high agreement* that the greatest barriers to long-term adaptation planning are incomplete knowledge of plant responses to CO_2 concentration and uncertainty in regionally-specific climate change scenarios (Medlyn *et al*., 2011b).

25.7.2. Agriculture

Australia produces 93% of its domestic food requirements yet still exports 76% of agricultural production (11.9% of total exports; DAFF, 2010). New Zealand agriculture contributes about 56% of total export value of which dairy products contribute 30% (Stats NZ, 2011c); 95% of all New Zealand dairy products are exported and these account for about 35% of world trade. Agricultural production is sensitive to climate (in particular to drought; see Box 25-5) but also to many non-climate factors, which thus far has limited detection or attribution of climate-related changes (7.2, although see Webb et al., 2012a). In New Zealand, the importance of agriculture makes the economy very sensitive to climate, for example an increase in soil moisture deficit has an immediate negative effect on domestic output and a consequent effect on GDP (Buckle *et al*., 2002)

25.7.2.1. Projected Impacts and Adaptation – Livestock Systems

Livestock grazing dominates land use by area in the region. At the Australian national level, the net effect of a 3°C temperature increase is expected to be a 4% reduction in gross value of the beef, sheep and wool sector due to declining rainfall and rising temperatures (McKeon et al., 2008). Dairy output is projected to decline in all regions of Australia other than Tasmania under a 1°C increase by 2030 (Hanslow *et al*., submitted). Projected changes in national pasture production for dairy, sheep and beef pastures in New Zealand range from an average reduction of 4% across climate scenarios for the 2030s (Wratt et al., 2008) to increases of up to 4% for two scenarios in the 2050s (Baisden *et al*., 2010), with increases based on more recent process-based models that incorporate CO_2 fertilisation and nitrogen feedbacks. An analysis of the impact of a 0.9-1.2°C increase on dairy systems across five sites in New Zealand found little change in operating profit over the period 2030-2049 (Lee et al., 2012).

Studies modelling seasonal (rather than annual average) changes in fodder supply show greater sensitivity in animal production to climate change and elevated CO_2 than previously anticipated and are expected to occur even under modest warming (*high confidence*) in both New Zealand (Lieffering *et al*., 2012) and Australia (Moore and Ghahramani, 2013). Across 25 sites in southern Australia (an area covering 85% of sheep and 40% of beef production regions), modelled profitability declined at most sites by the 2050s because of a shorter growing season (Moore and Ghahramani, 2013). Increasing soil fertility (largely using phosphate fertiliser) was an adequate adaptation until about 2050 but, thereafter, transformational change, such as enterprise choice, would be required to maintain incomes (Ghahramani and Moore, submitted). In New Zealand, projected changes in seasonal pasture growth drove changes in animal production at four sites representing the main areas of sheep production (Lieffering *et al*., 2012). In Hawke's Bay, changes in stock number were able to maintain farm income for a period in the face of variable forage supply but transformational adaptation would be required to maintain farm income in the longer term. In Southland and Waikato, projected increases in early spring pasture growth posed management problems in maintaining pasture quality, yet, if these were met, animal production could be maintained or increased.

Rainfall is a key determinant of inter-annual variability in production and profitability of pastures and rangelands (Radcliffe and Baars, 1987; Steffen *et al*., 2011) yet remains the most uncertain change. Savannahs that are currently water-limited are expected to show greater sensitivity to temperature and rainfall changes than nitrogen-limited ones (Webb *et al*., 2012b). The 'water-sparing' effect of elevated CO_2 (offsetting reduced water availability through reduced rainfall and increased temperatures) is invoked in many impact studies but reduced stomatal conductance does not always translate into production benefits (Kamman *et al*., 2005; Newton *et al*., 2006; Stokes and Ash, 2007; Wan *et al*., 2007). The impacts of elevated CO_2 on forage production, quality, nutrient cycling and water availability remains the major uncertainty in modelling system responses (McKeon *et al*., 2009). New Zealand agro-ecosystems are subject to erosion processes strongly driven by climate; greater certainty in projections of rainfall, particularly storm frequency, are needed to better understand climate change impacts on erosion (Basher et al., 2012).

25.7.2.2. Projected Impacts and Adaptation – Cropping

Experiments (Fitzgerald *et al*., 2010) and modelling for wheat in Australia (Crimp *et al*., 2008; Luo *et al*., 2009; O'Leary *et al*., 2010) and New Zealand (Teixeira *et al*., 2012) support the AR4 conclusion (Hennessy *et al*., 2007)

that adaptation, particularly altering sowing dates and cultivars, can sustain or increase yields past 2050 except under the most extreme low rainfall scenarios (*high confidence*). Although yields may increase in New Zealand with current management (Teixeira *et al*., 2012), adaptation will be essential in Australia to avoid yield reductions in some regions (Luo *et al*., 2009). Under the more severe climate scenarios and without adaptation, Australia could become a net importer of wheat (Howden *et al*., 2010).

Rice production in Australia is largely dependent on irrigation and climate change impacts will strongly depend on water availability and price (Gaydon *et al*., 2010). Sugarcane is also strongly water dependent (Carr and Knox, 2011); yields may increase where rainfall is unchanged or increased, but rising temperatures could drive up evapotranspiration and increase water use (*medium confidence*; Park *et al*., 2010).

Observed trends and modelling for wine-grapes suggest that climate change will lead to earlier budburst, ripening and harvest for most regions and scenarios (*high confidence*; Grace *et al*., 2009; Sadras and Petrie, 2011; Webb *et al*., 2012a). Without adaptation, reduced quality is expected in all Australian regions (*high confidence*; Webb *et al*., 2008). Change in cultivar suitability in specific regions is expected (Clothier *et al*., 2012), with potential for development of cooler or more elevated sites within some regions (Tait, 2008; Hall and Jones, 2009) and/or expansion to new regions, with some growers in Australia already relocating (e.g. to Tasmania; Smart, 2010).

Climate change and elevated CO_2 impacts on weeds, pests and diseases are highly uncertain (see Box 25.4). Future performance of currently effective resistance mechanisms under elevated CO_2 and temperature is particularly important (Melloy *et al*., 2010; Chakraborty *et al*., 2011) as is the future efficacy of biocontrol (Gerard *et al*., 2012), which is widely used in the region. Australia is ranked second and New Zealand fourth in the world in the number of biological control agent introductions (Cock *et al*., 2010).

25.7.2.3. Integrated Adaptation Perspectives

Future water demand by the sector is critical for planning (Box 25.2). Even though dryland agriculture dominates in Australia (DAFF, 2010), irrigation takes 50% of total water consumption (70% in the Murray-Darling Basin; Quiggin *et al*., 2008), and generates 30% of the gross value of Australian agriculture (Robertson, 2010). Reduced inflow under a non-mitigation scenario is predicted to reduce the value of agricultural production in the Basin by 12-44% to 2030 and 49-72% to 2050 (A1FI; Garnaut, 2008). Water availability also constrains agricultural expansion: 17 Mha in northern Australia could support cropping but only 1% has appropriate water availability (Webster *et al*., 2009). In New Zealand, the irrigated area has risen by 82% since 1999 to over 1 Mha; 76% is on pasture (Rajanayaka *et al*., 2010). The New Zealand dairy herd doubled between 1980-2009 moving from high rainfall zones (>2000 mm annual) to drier, irrigation-dependent areas (600-1000 mm annual); this dependence will increase with expansion (Robertson, 2010), which is being supported by the Government's Irrigation Acceleration Fund.

Many adaptation options such as flexible water allocation, irrigation and seasonal forecasting support managing risk in the current climate (Howden *et al*., 2008; Botterill and Dovers, 2013) and adoption is often high (Hogan *et al*., 2011a; Kenny, 2011). However, incremental on-farm adaptation has limits (Stafford-Smith *et al*., 2011a; Park *et al*., 2012) and may hinder transformational change such as diversification of land use or relocation (see Box 25-5) if it encourages persistence where climate change may take current systems beyond their response capacity (Marshall, 2010; Park *et al*., 2012; Rickards and Howden, 2012). In many cases, transformational change requires a greater level of commitment, access to more resources, and greater integration across levels of decision-making that encompass both on- and off-farm knowledge, processes and values (Marshall, 2010; Rickards and Howden, 2012).

_____ START BOX 25-4 HERE _____

Box 25-4. Biosecurity

Biosecurity is a high priority for Australia and New Zealand given the economic importance of biologically-based industries and risks to endemic species and iconic ecosystems. There is *high confidence* that the biology and

potential risk from invasive and native pathogenic species will be altered by climate change (Roura-Pascual *et al.*, 2011), but impacts may be positive or negative depending on the particular system.

[INSERT TABLE 25-4 HERE
Table 25-4: Examples of potential consequences of climate change for invasive and pathogenic species relevant to Australia and New Zealand, with consequence categories based on Hellman et al. (2008).]

_____ END BOX 25-4 HERE _____

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Box 25-5. Climate Change Vulnerability and Adaptation in Rural Areas

Rural communities in Australasia have higher proportions of older and unemployed people than urban populations (Mulet-Marquis and Fairweather, 2008). Employment and economic prospects depend heavily on the physical environment and hence are highly exposed to climate (averages, variability and extremes) as well as changing commodity prices. These interact with other economic, social and environmental pressures, such as changing government policies (e.g. on drought, carbon pricing; Productivity Commission, 2009; Nelson *et al.*, 2010) and access to water resources. The vulnerability of rural communities differs within and between countries reflecting differences in financial security, environmental awareness, policy and social support, strategic skills and capacity for diversification (Bi and Parton, 2008; Marshall, 2009; Nelson *et al.*, 2010; Hogan *et al.*, 2011b; Kenny, 2011).

Climate change will affect rural industries and communities through impacts on resource availability and distribution, particularly water. Decreased availability and/or increased demand, or price, in response to climate change will increase tensions among agricultural, mining, urban and environmental water users (*very high confidence*), with implications for governance and participatory adaptation processes to resolve conflicts (see 25.4.2, 25.4.3, 25.6.1, 25.7.2, 25.7.3, Box 25-2, Box 25-10). Communities will also be affected through direct impacts on primary production, extraction activities, critical infrastructure, population health and recreational and culturally significant sites (see 25.7, 25.8; Kouvelis *et al.*, 2010; Balston *et al.*, 2012).

Altered production and profitability risks and/or land use will translate into complex and interconnected effects on rural communities, particularly income, employment, service provision, and reduced volunteerism (Stehlik *et al.*, 2000; Bevin, 2007; Kerr and Zhang, 2009). The prolonged drought in Australia during the early 2000s, for example, had many interrelated negative social impacts in rural communities, including farm closures, increased poverty, increased off-farm work and, hence, involuntary separation of families, increased social isolation, rising stress and associated health impacts, including suicide (especially of male farmers), accelerated rural depopulation and closure of key services (*high agreement, robust evidence*; Alston, 2007; Edwards and Gray, 2009; Alston, 2010, 2012; Hanigan *et al.*, 2012). Positive social change also occurred, however, including increased social capital through interaction with community organisations (Edwards and Gray, 2009). While social and cultural changes have the potential to undermine the adaptive capacity of communities (Smith *et al.*, 2011b), robust ongoing engagement between farmers and the local community can contribute to a strong sense of community and enhance potential for resilience (McManus *et al.*, 2012).

The economic impact of droughts on rural communities and the entire economy can be substantial. The 2002-03 drought in Australia, for example, significantly reduced agricultural income and employment and subtracted around 1% from GDP (equivalent to A$7.4 billion; ABS, 2004), but the full impact may have been as high as 1.6% when indirect impacts are included (Horridge *et al.*, 2005). Widespread drought in New Zealand during 2007-2009 affected many regions not traditionally impacted by drought, such as the Waikato, resulting in an estimated reduction of NZ$3.6 billion in direct and off-farm output (Butcher, 2009). Drought frequency and severity are projected to increase in many parts of the region (Table 25-1).

The decisions of rural enterprise managers have significant consequences for and beyond rural communities (Pomeroy, 1996; Clark and Tait, 2008). Many current responses are incremental, responding to existing climate variability (Kenny, 2011), but transformational change has occurred where industries and individuals are relocating

part of their operations, e.g. rice (Gaydon *et al*., 2010), wine-grapes (Park *et al*., 2012), peanuts (Thorburn *et al*., 2012) or changing and diversifying land use *in situ* (e.g. the recent switch from grazing to cropping in South Australia; Howden *et al*., 2010) in response to recent and/or expectations of future climate or policy change (Kenny, 2011; see also Box 25-10). Such transformational changes are expected to become more frequent and widespread with a changing climate (*high confidence*; 25..6.2), with positive or negative implications for the wider communities in origin and destination regions.

Although stakeholders within rural communities differ in their vulnerabilities and adaptive capacities, they are bound by similar dependence upon critical infrastructure and resources, economic conditions, government policy direction, and societal expectations (Loechel *et al*., 2013). Consequently, adaptation to climate change will require an approach that devolves decision-making to the level where the knowledge for effective adaptations resides, using open communication, interaction and joint-planning (Nelson *et al*., 2008).

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Box 25-6. Climate Change and Fire

Fire during hot, dry and windy summers in southern Australia can cause loss of life and substantial property damage (Cary *et al*., 2003; Adams and Attiwill, 2010). The 'Black Saturday' bushfires in Victoria in February 2009, for example, burnt over 4,500 km^2, caused 173 deaths, destroyed over 2,000 buildings and caused damages of A$4billion (Cameron *et al*., 2009; VBRC, 2010). This fire occurred toward the end of a 13-year drought (CSIRO, 2010) and after an extended period of consecutive days over 40°C (Tolhurst, 2009).

Climate change is expected to increase the number of days with very high and extreme fire weather (Table 25-1), with greater changes where fire is weather-constrained (most of southern Australia; many, in particular eastern and northern, parts of New Zealand) than where it is constrained by fuel load and ignitions (tropical savannas in Australia). Fire season length will be extended in many already high-risk areas (*high confidence*) and so reduce opportunities for controlled burning (Lucas *et al*., 2007). Higher CO_2 will also generally enhance fuel loads except where moisture is limiting (Donohue *et al*., 2009; Williams *et al*., 2009; Bradstock, 2010; Hovenden and Williams, 2010; King *et al*., 2011).

Climate change and fire will have complex impacts on vegetation communities and biodiversity, with negative or positive implications in different regions (Williams *et al*., 2009). The greatest impacts on biodiversity in Australia are expected in the sclerophyll forests of the south-east and south-west (Williams *et al*., 2009). Most New Zealand native ecosystems have limited exposure but also limited adaptation to fire (Ogden *et al*., 1998; McGlone and Walker, 2011). There is *high confidence* that increased incidence of fires in southern Australia will increase risk to people, property and infrastructure such as electricity transmission lines (Parsons Brinkerhoff, 2009; O'Neill and Handmer, 2012; Whittaker *et al*., 2013) and in parts of New Zealand where urban margins expand into rural areas (Jakes *et al*., 2010; Jakes and Langer, 2012); exacerbate some respiratory conditions such as asthma (Johnston *et al*., 2002; Beggs and Bennett, 2011); and increase economic risks to plantation forestry (Watt *et al*., 2008; Pearce *et al*., 2011). Forest regeneration following wildfires also reduces water yields (Brown *et al*., 2005; MDBC, 2007), while reduced vegetation cover increases erosion risk and material washoff to waterways with implications for water quality (Shakesby *et al*., 2007; Wilkinson *et al*., 2009; Smith *et al*., 2011a).

In Australia, fire management will become increasingly challenging under climate change (*high confidence*; O'Neill and Handmer, 2012; Whittaker *et al*., 2013). Current initiatives centre on planning and regulations, building design to reduce flammability, fuel management, early warning systems, and fire detection and suppression (Handmer and Haynes, 2008; Preston *et al*., 2009; VBRC, 2010; O'Neill and Handmer, 2012). Some Australian authorities are taking climate change into account when rethinking approaches to managing fire to restore ecosystems while protecting human life and properties (Preston *et al*., 2009; Adams and Attiwill, 2010). Improved understanding of climate-drivers of fire risks is assisting fire management agencies, landowners and communities in New Zealand

(Pearce *et al*., 2008; Pearce *et al*., 2011), although changes in management to date show little evidence of being driven by climate change.

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25.7.3. Mining

Australia is the world's largest exporter of coking coal and iron ore and has the world's largest resources of brown coal, nickel, uranium, lead and zinc (ABS, 2012a). Recent events demonstrated significant vulnerability to climate extremes: the 2011 floods reduced coal exports by 25-54 million tonnes and led to A$5-9bn in lost revenue in that year (ABARES, 2011b; RBA, 2011). Impacts were exacerbated by regulatory constraints on mine discharges, highlighting tensions among industry, social and ecological management objectives (QRC, 2011).

Projected changes in climate extremes imply increasing sector vulnerability without adaptation (*high confidence*; Hodgkinson *et al*., 2010a; Hodgkinson *et al*., 2010b). Stakeholders perceive the adaptive capacity of the industry to be high (Hodgkinson *et al*., 2010a; Loechel *et al*., 2010; QRC, 2011), but costs and broader benefits are yet to be explored along the value-chain and evaluated for community support. On-going and open challenges include competition for energy and water, climate scepticism, avoiding maladaptation, and mining-community relations regarding response options, acceptable mine discharges and post-mining rehabilitation (Loechel *et al*., 2013).

25.7.4. Energy Supply, Demand and Transmission

Primary energy demand is projected to grow by 0.5-1.3% per annum in Australasia over the next few decades (MED, 2011; Syed, 2012). Australia's predominantly thermal power generation is vulnerable to drought-induced water restrictions, which could require dry-cooling and increased water use efficiency where rainfall declines (Graham *et al*., 2008; Smart and Aspinall, 2009). Depending on carbon price and technology costs, renewable electricity generation in Australia is projected to increase from 10% in 2010/11 to 19-50% by 2030 (Hayward *et al*., 2011; Stark *et al*., 2012; Syed, 2012), but few studies have explored the climate vulnerability of these new energy sources (Bryan *et al*., 2010; Crook *et al*., 2011; Odeh *et al*., 2011).

New Zealand's predominantly hydroelectric power generation is vulnerable to precipitation variability. Increasing winter precipitation and snow melt, and a shift from snowfall to rainfall will reduce this vulnerability (*medium confidence*) as winter/spring inflows to main hydro lakes are projected to increase by 5-10% over the next few decades (McKerchar and Mullan, 2004; Poyck *et al*., 2011). Further reductions in seasonal snow and glacial melt as glaciers diminish, however, would compromise this benefit (Chinn, 2001; Renwick *et al*., 2009; Srinivasan *et al*., 2011). Increasing wind power generation (MED, 2011) would benefit from projected increases in mean westerly winds but face increased risk of damages and shut-down during extreme winds (Renwick *et al*., 2009).

Climate warming would reduce annual average peak electricity demands by 1-2% per °C across New Zealand and 2(±1)% in New South Wales, but increase by 1.1(±1.4) and 4.6(±2.7)% in Queensland and South Australia due to air conditioning demand (Stroombergen *et al*., 2006; Jollands *et al*., 2007; Thatcher, 2007; Chen and Lie, 2010). Increased summer peak demand (see also Figure 25-5) will place additional stress on networks, particularly in Australia (*very high confidence*; Jollands *et al*., 2007; Thatcher, 2007; Howden and Crimp, 2008; Wang *et al*., 2010a). During the 2009 Victorian heat wave, for example, demand rose by 24% but electrical losses from transmission lines increased by 53% due to higher peak currents (Nguyen *et al*., 2010), and successive failures of the overloaded network temporarily left more than 500,000 people without power (QUT, 2010). Various adaptation options to limit increasing urban energy demand exist and some are being implemented (see Box 25-9).

There is *limited evidence* but *high agreement* that without additional adaptation, distribution networks in most Australian states will be at high risk of failure by 2031-2070 under non-mitigation scenarios due to increased bushfire risk and potential strengthening and southward shift of severe cyclones in tropical regions (Maunsell and CSIRO, 2008; Parsons Brinkerhoff, 2009). Adaptation costs have been estimated at A$2.5 billion to 2015, with

more than half to meet increasing demand for air conditioning and the remainder to increase resilience to climate-related hazards; underground cabling would reduce bushfire risk but has large investment costs (not included above; Parsons Brinkerhoff, 2009). Decentralised ownership of assets constitutes a significant adaptation constraint (ATSE, 2008; Parsons Brinkerhoff, 2009). In New Zealand, increasing high winds and temperatures have been identified qualitatively as the most relevant risks to transmission (Jollands *et al*., 2007; Renwick *et al*., 2009).

25.7.5. Tourism

Tourism contributes 2.6-4% of GDP to the economies of Australia and New Zealand (ABS, 2010b; Stats NZ, 2011a). The net present value of the Great Barrier Reef alone over the next 100 years has been estimated at A$51.4 billion (Oxford Economics, 2009). Most Australasian tourism is exposed to climate variability and change, and some destinations are highly sensitive to extreme events (Becken and Hay, 2012). The 2011 floods and Cyclone Yasi, for example, cost the Queensland tourism industry about A$590 million, mainly due to cancellations and damage to the Great Barrier Reef (PWC, 2011), and drought in the Murray-Darling Basin caused an estimated A$70 million loss in 2008 due to reduced visitor days (TRA, 2010).

25.7.5.1. Projected Impacts

Future impacts on tourism have been modelled for several Australian destinations. The Great Barrier Reef is expected to degrade under all climate change scenarios (Box CC-CR, 25.6.2, 30.5), reducing its attractiveness (Marshall and Johnson, 2007; Bohensky *et al*., 2011; Wilson and Turton, 2011). Ski tourism is expected to decline in the Australian Alps due to snow cover reducing more rapidly than in New Zealand (Pickering *et al*., 2010; Hendrikx *et al*., in press) and greater perceived broad attractiveness of New Zealand (Hopkins *et al*., 2012). Higher temperature extremes in the Northern Territory are projected with *high confidence* to increase heat stress and incur higher costs for air conditioning (Turton *et al*., 2009). Sea level rise places pressures on shorelines and long-lived infrastructure but implications for tourist resorts have not been quantified (Buckley, 2008).

Economic modelling suggests that the Australian alpine region would be most negatively affected in relative terms due to limited alternative activities (Pham *et al*., 2010), whereas the competitiveness of some destinations (e.g. Margaret River in Western Australia) could be enhanced by higher temperatures and lower rainfall (Jones *et al*., 2010; Pham *et al*., 2010). An analogue-based study suggests that, in New Zealand, warmer and drier conditions mostly benefit but wetter conditions and extreme climate events undermine tourism (Wilson and Becken, 2011). *Confidence* in outcomes is *low* due to uncertain future tourist behaviour (Scott *et al*., 2012; also 25.9.2).

25.7.5.2. Adaptation

Both New Zealand and Australia have adaptation strategies for tourism (Becken and Clapcott, 2011; Zeppel and Beaumont, 2011); promoted preparation for extreme events (Tourism Queensland, 2007, 2010; Tourism Victoria, 2010); and are strengthening ecosystem resilience to maintain destination attractiveness (GBRMPA, 2009). Snow-making is already broadly adopted to increase reliability of skiing (Bicknell and McManus, 2006; Hennessy *et al*., 2008b), but its future effectiveness depends on location. In New Zealand, even though warming will significantly reduce the number of days suitable for snow-making (Hendrikx and Hreinsson, 2012), sufficient snow could be made in all years until the end of the 21st century to maintain current minimum operational skiing conditions. Options for resorts in Australia's Snowy Mountains are far more limited (Hendrikx *et al*., in press), where maintaining skiing conditions until at least 2020 would require A$100 million in capital investment into 700 snow guns and 2.5-3.3 GL of water per month (Pickering and Buckley, 2010).

Short investment horizons, high substitutability and a high proportion of human capital compared with built assets give *high confidence* that the adaptive capacity of the tourism industry is high overall, except for destinations where climate change is projected to degrade core natural assets and diversification opportunities are limited (Evans *et al*., 2011; Morrison and Pickering, 2011). Strategic adaptation decisions are constrained by uncertainties in regional

climatic changes (Turton *et al*., 2010), limited concern (Bicknell and McManus, 2006), lack of leadership and limited coordinated forward planning (Sanders *et al*., 2008; Turton *et al*., 2009; Roman *et al*., 2010; White and Buultjens, 2012). An integrated assessment of tourism vulnerability in Australasia is not yet possible due to limited understanding of future changes in tourism and community preferences (Scott *et al*., 2012), including the flow-on effects of changing travel behaviour and tourism preferences in other world regions (see 25.9.2).

25.8. Human Society

25.8.1. Human Health

25.8.1.1. Observed Impacts

Life expectancy in Australasia is high, but shows substantial ethnic and socio-economic inequalities (Anderson *et al*., 2006b). There is *high agreement and robust evidence* that mortality increases in hot weather (Bi and Parton, 2008; Vaneckova *et al*., 2008) with air pollution exacerbating this association. Exceptional heatwave conditions in Australia have been associated with substantial increases in mortality and hospital admissions in several capital cities (*high confidence*; Khalaj *et al*., 2010; Loughnan *et al*., 2010; Tong *et al*., 2010a; Tong *et al*., 2010b). In January and February 2009, for example, south-eastern Australia experienced record maximum temperatures and consecutive hot days in many locations (BoM, 2009). Over this period, total emergency cases increased by 25% and by 46% over the three hottest days. Direct heat-related health problems increased 34-fold, 61% of these being people aged 75 years or older. There were 374 excess deaths, a 62% increase in all-cause mortality (Victorian Government, 2009a). Mental health admissions increased by 7.3% in metropolitan South Australia during heatwaves (1993-2006), with increases across all age groups (Hansen *et al*., 2008). Mortality attributed to mental and behavioural disorders increased in the 65 to 74-year age group and in persons with schizophrenia, schizotypal, and delusional disorders (Hansen *et al*., 2008). Experience of extreme events also correlates strongly with general concern about climate change and psychological well-being (see 25.4.3).

25.8.1.2. Projected Impacts

Projected increases in heatwaves (see Figure 25-5) will increase both heat-related deaths and hospitalizations, especially among the elderly, compounded by population growth and ageing (*high confidence*). This may be partly offset by reduced deaths from cold at least for modest rises in temperature in the southern states of Australia and parts of New Zealand (*low confidence*; Bambrick *et al*., 2008; Kinney, 2012). Relative to a baseline that allowed for demographic change but no climate change after 2005, the annual net change across Australia was 943 (-11%) *fewer* deaths in 2070 and 924 (-11%) fewer in 2100 in a strongly mitigated 450 ppm scenario, or an *additional* 1250 (+14%) deaths in 2070 and 8628 (+100%) in 2100 in a hot, dry A1FI scenario (Bambrick *et al*., 2008). In this study, which accounted for changes in the mean but not variability of temperatures, net results were driven almost entirely by increased mortality in the north, especially Queensland, consistent with Huang *et al*., (2012) who projected temperature-related years of life lost in Brisbane. In a separate study, which did account for increased daily temperature variability, a substantial increase in heat-related deaths was estimated for Sydney (Gosling *et al*., 2009): using the HadCM3 climate model for both recent past and future climates, without adaptation, annual heat-related deaths per 100,000 people were projected to increase nearly threefold, from 2.5 in 1961-1990 to 7.4 in 2070-2099 for the A2 emissions scenario, and from 2.6 to 6.8 for the B2 scenario. The annual number of temperature-related hospital admissions in South Australia under the A1FI scenario is projected to increase 110% by 2100 (Bambrick *et al*., 2008). The number of hot days when physical labor in the sun becomes dangerous is also projected to increase substantially in Australia by 2070, leading to economic costs from lost productivity, increased hospitalisations and occasional deaths (*medium confidence*; Hanna *et al*., 2011; Maloney and Forbes, 2011).

Water- and food-borne diseases are projected to increase, but the complexity of their relationship to climate and non-climate drivers means there is *low confidence* in specific projections. For Australia, 205,000-335,000 new cases of bacterial gastroenteritis by 2050, and 239,000-870,000 cases by 2100, were projected under a range of emission scenarios (Bambrick *et al*., 2008; Harley *et al*., 2011). Water-borne zoonotic diseases such as cryptosporidiosis have

more complex relationships with climate (Lal *et al*., 2012), while water treatment systems help to prevent outbreaks related to heavy rainfall or flooding (Britton *et al*., 2010b, a).

Current empirical models assess the combined effects of climate change and socio-economic development on the distribution of vector borne diseases. The area climatically suitable for transmission of dengue is projected to expand under A1FI scenarios in Australia (*high confidence*; Bambrick *et al*., 2008). This expansion may be limited or even reversed depending on socio-economic development (*low confidence*; Åström *et al*., 2013). Australasia is projected to remain malaria free under the A1B emission scenario until at least 2050 (Béguin *et al*., 2011) and sporadic cases could be treated effectively. The impacts of climate change on Ross River and other arboviruses with more complex transmission cycles that involve multiple host species have not been modelled in this region. However, the combined effects of climate change, frequent travel within and outside the region, and recent incursions of exotic mosquito species suggest that the geographic range of arboviruses could expand (*medium confidence*; Derraik and Slaney, 2007; Derraik *et al*., 2010).

A growing literature since the AR4 has focused on the psychological impacts of climate change, based on impacts of recent climate variability and extremes (Doherty and Clayton, 2011; 25.4.3). These studies indicate significant mental health risks associated with climate-related disasters, in particular persistent and severe drought, floods and storms, and that impacts may be especially acute in rural communities where climate change places additional stresses on livelihoods (*high confidence*; Edwards *et al*., 2011; see also Box 25.5). Projected population growth and urbanization could further increase health risks indirectly via climate-related stress on housing, transport and energy infrastructure and water supplies (*low confidence*; Howden-Chapman, 2010).

[INSERT FIGURE 25-5 HERE
Figure 25-5: Projected changes in exposure to heat under a high emissions scenario (A1FI). Maps show the average number of days with peak temperatures >40°C for Australian statistical local areas, for ~1990 (based on available meteorological station data for the period 1975-2004), ~2050 and ~2100. Bar charts show the change in population heat exposure, expressed as person-days exposed to peak temperatures >40°C, aggregated by State/Territory and including projected population growth for a default scenario. Future temperatures are based on simulations by the GFDL-CM2 global climate model (Meehl *et al*., 2007), re-scaled to the A1FI scenario; simulations based on other climate models could give higher or lower results. Data from Baynes *et al*. (2012).]

25.8.1.3. Adaptation

Research since the AR4 has mainly focused on health impacts. Some adaptation strategies have received attention in Australia, however, including reshaping government policy, improving healthcare services, social support for those most at risk, improving community awareness to reduce adverse exposures, and developing early warning and emergency response plans (Wang and McAllister, 2011). In New Zealand, central Government health policies show no specific measures to adapt to climate change (Wilson, 2011).

A review of the southern Australian heatwave of 2009 identified communication failures with no clear public information or warning strategy, no clear thresholds for initiating public information campaigns or incident response resulting in mixed messages to the media and public (Kiem *et al*., 2010). Emergency and services infrastructure were underprepared and relied on reactive solutions (QUT, 2010). Charging more for energy during peak times would reduce risk to infrastructure overload (see 25.7.4), but leave low-income residents more vulnerable to heat waves (Strengers and Maller, 2011). The Victorian government has since developed a heatwave plan to coordinate a state-wide response, maintain consistent community-wide understanding through a Heat Health alert system, build capacity of councils to support communities most at risk from heat-related impacts, support and fund health services and a Heat Health Intelligence surveillance system, and distribute public health information (Victorian Government, 2009b). As a longer term strategy, greening cities reduces the urban heat island effect which in turn reduces heat health risks (Bambrick *et al*., 2011; see Box 25-9). The increased risk of dengue from domestic water tanks suggests a risk of maladaptive outcomes unless climate-related risks are taken into account in their installation and maintenance (Kearney *et al*., 2009).

25.8.2. Indigenous Peoples

25.8.2.1. Aboriginal and Torres Strait Islanders

Australia's Indigenous population is small (2.5%), widely dispersed and rapidly growing (ABS 2009) yet controls more than 25% of the Australian land area (Altman *et al*., 2007; NNTT, 2013). Key work since the AR4 includes a national Indigenous adaptation research action plan (Langton *et al*., 2012), regional risk studies (Green *et al*., 2009; DoNP 2010; TSRA 2010) and scrutiny from an Indigenous rights perspective (ATSISJC 2009).

Socio-economic disadvantage and poor health (SCRGSP 2011) indicate a disproportionate climate change vulnerability of Indigenous Australians (McMichael *et al*., 2009) although there are no detailed assessments. In urban and regional areas, where 75% of the Indigenous population lives, assessments have not specifically addressed risks to Indigenous people (e.g. Guillaume *et al*., 2010). In other regions, all remote, there is limited empirical evidence of vulnerability (Maru *et al*., 2012). However, there is *high agreement* and *medium evidence* for significant future impacts from increasing heat stress, extreme events and increased disease (Campbell *et al*., 2008; Spickett *et al*., 2008; Green *et al*., 2009).

There is also *high agreement* but *limited evidence*, that: natural resource dependence (e.g. Bird *et al*., 2005; Gray *et al*., 2005a; Kwan *et al*., 2006; Buultjens *et al*., 2010) increases Indigenous exposure and sensitivity to climate change (Green *et al*., 2009); climate change-induced dislocation, attenuation of cultural attachment to place and loss of agency will disadvantage Indigenous mental health and community identity (Fritze *et al*., 2008; Hunter, 2009; McIntyre-Tamwoy and Buhrich, 2011); and, housing, infrastructure, services and transport, often already inadequate for Indigenous needs especially in remote Australia (ABS 2010c), will be further stressed (Taylor and Philp, 2010). Torres Strait island communities and livelihoods are vulnerable to major impacts from even small sea level rises (*high confidence*; DCC, 2009; Green *et al*., 2010b; TSRA 2010).

Little adaptation of Indigenous communities to climate change is apparent to date (but see Burroughs, 2010; GETF 2011). Institutions external to Indigenous communities can constrain their adaptive capacity (Ellemor, 2005; Petheram *et al*., 2010; Veland *et al*., 2010; Langton *et al*., 2012) and designing and communicating adaptation strategies is challenged by multiple stressors. Adaptation planning would benefit from a robust typology (Maru *et al*., 2011) across the diversity of Indigenous life experience (McMichael *et al*., 2009). Indigenous re-engagement with environmental management (e. g. Hunt *et al*., 2009; Ross *et al*., 2009) can promote health (Burgess *et al*., 2009) and may increase adaptive capacity (Berry *et al*., 2010; Davies *et al*., 2011). There is emerging interest in integrating Indigenous observations of climate change (Green *et al*., 2010c; Petheram *et al*., 2010) and developing inter-cultural communication tools (Prober *et al*., 2011; Woodward *et al*., 2012). Extensive land ownership in northern and inland Australia and land management traditions mean that Indigenous people are well situated to provide greenhouse gas abatement and carbon sequestration services that may also support their livelihood aspirations (Whitehead *et al*., 2009; Heckbert *et al*., 2012).

25.8.2.2. New Zealand Māori

The projected impacts of climate change on Māori society are expected to be highly differentiated reflecting complex economic, social, cultural, environmental and political factors (*high confidence*). Since the AR4, studies have been either sector-specific (e.g. Insley, 2007; Insley and Meade, 2008; Harmsworth *et al*., 2010; King *et al*., 2012) or more general, inferring risk and vulnerability based on exploratory engagements with varied stakeholders and existing social, economic, political and ecological conditions (e.g. MfE, 2007b; Te Aho, 2007; King *et al*., 2010).

The Māori economy depends on climate-sensitive primary industries with vulnerabilities to climate conditions (*high confidence*; Packman *et al*., 2001; NZIER, 2003; Cottrell *et al*., 2004; TPK, 2007; Tait *et al*., 2008b; Harmsworth *et al*., 2010; King *et al*., 2010; Nana *et al*., 2011a). Much of Māori-owned land is steep (>60%) and susceptible to damage from high intensity rainstorms, while many lowland areas are vulnerable to flooding and sedimentation (Harmsworth and Raynor, 2005; King *et al*., 2010). Land in the east and north is also drought prone, and this

increases uncertainties for future agricultural performance, product quality and investment (*medium confidence*; Cottrell *et al*., 2004; Harmsworth *et al*., 2010; King *et al*., 2010). The fisheries and aquaculture sector faces substantial risks (and uncertainties) from changes in ocean temperature and chemistry, potential changes in species composition, condition and productivity levels (*medium confidence*; King *et al*., 2010; see also 25.6.2). At the community and individual level, Māori regularly utilize the natural environment for hunting and fishing, recreation, the maintenance of traditional skills and identity, and collection of cultural resources (King and Penny, 2006; King *et al*., 2012). Many of these activities are already compromised due to resource-competition, degradation and modification (Woodward *et al*., 2001; King *et al*., 2012). Climate change driven shifts in natural ecosystems will further challenge the capacities of some Māori to cope and adapt (*medium confidence*; King *et al*., 2012).

Māori organizations have sophisticated business structures, governance (e.g. trusts, incorporations) and networks (e.g. Iwi leadership groups) across the state and private sectors (Harmsworth *et al*., 2010; Insley, 2010; Nana *et al*., 2011b), critical for managing and adapting to climate change risks (Harmsworth *et al*., 2010; King *et al*., 2012). Some tribal organizations are developing options in response to the New Zealand Government's Emissions Trading Scheme (Insley, 2010). Future opportunities will depend on partnerships in business, science, research and government (*high confidence*; Harmsworth *et al*., 2010; King *et al*., 2010) as well as innovative technologies and new land management practices to better suit future climates (Carswell *et al*., 2002; Harmsworth, 2003; Funk and Kerr, 2007; Insley and Meade, 2008; Tait *et al*., 2008b; Penny and King, 2010).

Māori knowledge of environmental processes and hazards (King *et al*., 2005; King *et al*., 2007) as well as strong social-cultural networks are vital for adaptation and on-going risk management (King *et al*., 2008); however, choices and actions continue to be constrained by insufficient resourcing, shortages in social capital, and competing values (King *et al*., 2012). Combining traditional ways and knowledge with new and untried policies and strategies will be key to the long-term sustainability of climate-sensitive Māori communities, groups and activities (*high confidence*; Harmsworth *et al*., 2010; King *et al*., 2012).

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Box 25-7. Insurance as Climate Risk Management Tool

Insurance helps spread the risk from extreme events across communities and over time and therefore enhances the resilience of society to disasters (see 10.7). In Australia, insured losses are dominated by meteorological hazards, including the 2011 Queensland floods and the 1999 Sydney hailstorm (ICA, 2012) with estimated claims of A$3 billion p.a. (IAA, 2011a). In New Zealand, floods and storms are the second most costly natural hazards after earthquakes (ICNZ, 2013). Even though the number of damaging insured events (up to a certain loss value) has increased significantly in the Oceania region since 1980 (Schuster, 2013), normalised insured losses in Australia show no significant trend from 1967 to 2006 (Crompton and McAneney, 2008; see also Table 10.4).

There is *high confidence* that without adaptive measures, projected increases in extremes (Table 25-1) and uncertainties in these projections will lead to increased insurance premiums, exclusions and non-coverage in some locations (IAG, 2011), which will reshape the distribution of vulnerability, e.g., through unaffordability or unavailability of cover in areas at highest risk (IAA, 2011a, b; NDIR, 2011; Booth and Williams, 2012). Restriction of cover occurred in some locations following recent flood events in Queensland (Suncorp, 2013).

Insurance can positively contribute to risk reduction by providing incentives to policy holders to reduce their risk profile (O'Neill and Handmer, 2012), e.g. through resilience ratings given to buildings (TGA, 2009; Edge Environment, 2011; IAG, 2011). Apart from constituting an autonomous private sector response to extreme events, insurance can also be framed as a form of social policy to manage climate risks, similar to New Zealand's government insurance scheme to manage geological risk (Glavovic *et al*., 2010); government measures to reduce or avoid risks also interact with insurance companies' willingness to provide cover (Booth and Williams, 2012). Insurance can also act as a barrier to adaptation, however, where those living in climate-risk prone localities pay discounted or cross-subsidised premiums, or if policies fail to encourage betterment after damaging events by requiring replacement of 'like for like', constituting a missed opportunity for risk reduction (NDIR, 2011; QFCI, 2012; Reisinger *et al*., 2013; see also 10.7).

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Box 25-8. Changes in Flood Risk and Management Responses

Floods are the most costly natural disaster in Australia (BTE, 2001) and the second-most costly insured disaster in New Zealand, after earthquakes (ICNZ, 2013). Nonetheless, flood damages across eastern Australia and both main islands of New Zealand in 2010 and 2011 revealed a significant adaptation deficit (ICA, 2012; ICNZ, 2013). For example, the Queensland floods in January 2011 resulted in 35 deaths, three quarters of the State including Brisbane declared a disaster zone, and damages in excess of AUD$2 billion (Queensland Government, 2011). These floods were associated with a strong monsoon and the strongest La Niña on record (Cai *et al*., 2012; CSIRO and BoM, 2012; Evans and Boyer-Souchet, 2012). Floods exhibit strong decadal variability in their frequency and severity but no significant long-term trend to date (Kiem *et al*., 2003; Smart and McKerchar, 2010; Ishak *et al*., in press).

Flood risk is projected to increase in many regions due to more intense extreme rainfall events driven by a warmer and wetter atmosphere (*medium confidence*; Table 25-1). High resolution downscaling (Griffiths, 2007; Carey-Smith *et al*., 2010), and dynamic catchment hydrological and river hydraulic modelling in New Zealand (Gray *et al*., 2005b; McMillan *et al*., 2010; MfE, 2010a; Ballinger *et al*., 2011; Duncan and Smart, 2011; McMillan *et al*., 2012) indicate that the 50-year and 100-year flood peaks for rivers in many parts of the country will increase by 10-20% by 2050 and more (and greater variation between models and scenarios) by 2100, with a corresponding decrease in return periods for design floods. Studies for Queensland show similar results (DERM *et al*., 2010). In Australia, flood risk is expected to increase more in the north (driven by convective rainfall systems) than in the south (where more intense extreme rainfall may be compensated by drier antecedent moisture conditions), consistent with confidence in heavy rainfall projections (Table 25-1; Alexander and Arblaster, 2009; Rafter and Abbs, 2009a).

Flood risk near river mouths will be exacerbated by storm surge associated with higher sea level and potential change in wind speeds (McInnes *et al*., 2005; MfE, 2010a; Wang *et al*., 2010b). Higher rainfall intensity and peak flow will also increase erosion and sediment loads in waterways (Nearing *et al*., 2004) and exacerbate problems from aging stormwater and wastewater infrastructure in cities (Howe *et al*., 2005; Jollands *et al*., 2007; CCC, 2010; WCC, 2010). However, moderate flooding also has benefits through filling reservoirs, recharging groundwater and replenishing natural environments (Hughes, 2003; Chiew and Prosser, 2011; Oliver and Webster, 2011).

Adaptation to increased flood risks from climate change is starting to happen (Wilby and Keenan, 2012) through updating guidelines for design flood estimation (MfE, 2010a; Westra, 2012), improving flood risk management (O'Connell and Hargreaves, 2004; NFRAG, 2008; Queensland Government, 2011), enhancing coping capacity for buildings in flood prone areas (options include raising floor levels, using strong piled foundations, using water-resistant insulation materials and ensuring weather tightness), and risk reduction and avoidance through spatial planning and managed relocation (Trotman, 2008; Glavovic *et al*., 2010; LVRC, 2012; QFCI, 2012). Adaptation options in urban areas include retaining floodplains and floodways and retrofitting existing systems to attenuate flows (Box 25.9; Howe *et al*., 2005; Skinner, 2010; WCC, 2010).

The recent flooding in eastern Australia and the projected increase in future flood risk have resulted in changes to reservoir operations to mitigate floods (van den Honert and McAneney, 2011; QFCI, 2012) and insurance practice to cover flood damages (NDIR, 2011; Phelan, 2011). However, the magnitude of potential future changes in flood risks and limits to incremental adaptation responses in urban areas suggest that more transformative and structural approaches based on altering land-use and avoidance of exposure to future flooding may be needed in some locations, especially if changes in the upper range of projections are realised (*high confidence*; Lawrence and Allan, 2009; DERM *et al*., 2010; Glavovic *et al*., 2010; Wilby and Keenan, 2012; Lawrence *et al*., submitted-a).

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Box 25-9. Opportunities, Constraints, and Challenges to Adaptation in Urban Spaces

Considerable opportunities exist for Australasian cities and towns to reduce climate change impacts and, in some regions, benefit from projected changes such as warmer winters and more secure water supply (Fitzharris, 2010; Australian Government, 2012). Many tools and practices developed for sustainable resource management or disaster risk reduction in urban areas are co-beneficial for climate change adaptation, and vice versa, and can be integrated with mitigation objectives (Hamin and Gurran, 2009). Despite the abundance of potential adaptation options, however, social, cultural, institutional and economic factors frequently constrain their implementation (*robust evidence* and *high agreement*; see also 25.4.2). The form and longevity of cities and towns, with their concentration of hard and critical infrastructure such as housing, transport, energy transmission, waste, telecommunications and public facilities provide additional challenges (see also Chapters 8 and 10, Boxes 25-1, 25-2, 25-8, 25.7.4, 25.8.1). Table 25-5 summarises some adaptation options, co-benefits and constraints on their adoption in Australasia.

Overall, the implementation of climate change adaptation policy for urban settlements in Australia and New Zealand has been mixed. The Australian National Urban Policy encourages adaptation, and many urban plans include significant adaptation policies (City of Melbourne, 2009; City of Port Phillip, 2010; e.g. ACT Government, 2012; City of Adelaide, 2012). New Zealand also promotes urban adaptation through strategies, plans and guidance documents (MfE, 2008a; CCC, 2010; WCC, 2010; Auckland Council, 2012). Many examples of incremental urban adaptation exist already (see Box 25-2, Table 25-5), particularly where these include co-benefits and respond to other stressors, like prolonged drought in southern Australia and recurrent floods. Experience is much scarcer with transformative changes, such as managed relocation or more flexible land-uses that could disrupt existing settlement patterns and development trends, and where maintaining flexibility to address long-term climate risks can run against near-term development pressures (see Boxes 25-2, 25-8). Decision-making models that support adaptive and transformative change (25.4.2) have not yet been implemented widely in urban contexts; increased coordination among different levels of government may be required to spread costs and balance public and private, near- and long-term and local and regional benefits (Norman, 2009; Britton, 2010; Norman, 2010; Abel *et al.*, 2011; McDonald, 2013; Palutikof *et al.*, 2013; Reisinger *et al.*, 2013; Lawrence *et al.*, submitted-a).

[INSERT TABLE 25-5 HERE
Table 25-5: Examples of co-beneficial climate change adaptation options for urban areas and barriers to their adoption. Options in italics are already widely implemented in Australia and New Zealand urban areas.]

_____ END BOX 25-9 HERE _____

25.9. Interactions among Impacts, Adaptation, and Mitigation Responses

The AR4 found that individual adaptation responses can entail synergies or trade-offs with other adaptation responses and with mitigation, but that integrated assessment tools were lacking in Australasia (Hennessy *et al.*, 2007). Subsequent studies provide detail on such interactions and can inform a balanced portfolio of climate change responses, but evaluation tools remain limited, especially for local decision-making (Park *et al.*, 2011). A review of 25 specific climate change-associated land-use plans from Australia, for example, found that 12 exhibited potential for conflict between mitigation and adaptation (Hamin and Gurran, 2009).

25.9.1. Interactions among Local-Level Impacts, Adaptation, and Mitigation Responses

Table 25-6 shows examples of adaptation responses that are either synergistic or entail trade-offs with other impacts and/or adaptation responses and goals. Adapting proactively to projected climate changes, particularly extremes such as floods or drought, can increase near-term resilience to climate variability and be a motivation for adopting adaptation measures (Productivity Commission, 2012). However, exclusive reliance on near-term benefits can increase trade-offs and result in long-term maladaptation (*high confidence*). For example, enhancing protection

measures after major flood events, combined with rapid re-building, accumulates fixed assets that can become increasingly costly to protect as climate change continues, with attendant loss of amenity and environmental values (Glavovic *et al.*, 2010; Gorrdard *et al.*, 2012; McDonald, 2013). Similarly, deferring adoption of increased design wind speeds in cyclone-prone areas delays near-term investment costs but also reduces the long-term benefit/cost ratio of the strategy (Stewart and Wang, 2011).

[INSERT TABLE 25-6 HERE
Table 25-6: Examples of interactions between impacts and adaptation measures in different sectors. In each case, impacts or responses in one sector have the potential to cause negative impacts or have co-benefits with impacts or responses in another sector, or with another type of response in the same sector.]

Mitigation actions can contribute to but also counteract local adaptation goals. Energy efficient buildings, for example, reduce network and health risks during heat waves, but urban densification to reduce transport energy demand intensifies urban heat islands and, hence, heat-related health risks (25.7.4, 25.8.1). Specific adaptations can also make achievement of mitigation targets harder or easier. Increased use of air conditioning, for example, increases energy demand, but reducing heat exposure through energy efficiency and building design reduces demand (25.7.4, Box 25-9). Table 25-7 gives further examples, and Box 25-10 explores the multiple and complex benefits and trade-offs in changing land-use simultaneously to adapt to and mitigate climate change.

[INSERT TABLE 25-7 HERE
Table 25-7: Examples of interactions between adaptation and mitigation measures (green rows denote synergies where multiple benefits may be realized, orange rows denote potential tradeoffs and conflicts; grey row gives an example of complex, mixed interactions). The primary goal may be adaptation or mitigation.]

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Box 25-10. Land-based Interactions Among Climate, Energy, Water, and Biodiversity

Climate, water, biodiversity, food and energy production and use are intertwined through complex feedbacks and trade-offs (see also Box CC-WE). This could make alternative uses of natural resources within rural landscapes increasingly contested, yet decision support tools to manage competing objectives are limited (PMSIEC, 2010).

Various policies in Australasia support increased biofuel production and biological carbon sequestration via, for example, mandatory renewable energy targets and incentives to increase carbon storage. Impacts of increased biological sequestration activities on biodiversity depend on their implementation. Benefits arise from reduced erosion, additional habitat, and enhanced ecosystem connectivity, while risks or lost opportunities are associated with large-scale monocultures especially if replacing more diverse landscapes (Brockerhoff *et al.*, 2008; Giltrap *et al.*, 2009; Steffen *et al.*, 2009; Todd *et al.*, 2009; Bradshaw *et al.*, submitted).

Photosynthesis transfers water to the atmosphere, so increased sequestration is projected to reduce catchment yields particularly in southern Australia and affect water quality negatively (Botkin *et al.*, 2007; CSIRO, 2008; Schrobback *et al.*, 2011; Bradshaw *et al.*, submitted). Accounting for this water use in water allocations for sequestration activities would increase their cost and limit the potential of sequestration-driven land-use change (Polglase *et al.*, 2011; Stewart *et al.*, 2011). Large-scale land-cover changes also affect regional climate through changing albedo, evapotranspiration and surface roughness, but these feedbacks have rarely been integrated with direct water demands (McAlpine *et al.*, 2009; Kirschbaum *et al.*, 2011b).

Biological carbon sequestration in New Zealand is less water-challenged than in Australia, except where catchments are projected to become drier and/or are already completely allocated (MfE, 2007a; Rutledge *et al.*, 2011). Carbon sequestration would mostly improve water quality through reduced erosion (Giltrap *et al.*, 2009). Policies to protect water quality by limiting nitrogen discharge from agriculture have reduced livestock production and greenhouse gas emissions in the Lake Taupo catchment and supported land-use change towards sequestration (Yeo *et al.*, 2012).

Trade-offs between biofuel and food production and ecosystem services depend strongly on the type of sequestration activity and their management relies on use of consistent principles to evaluate externalities and benefits of alternative land-uses (PMSIEC, 2010). First-generation biofuels have been modelled in Australia as directly competing with agricultural production (Bryan *et al*., 2010). In contrast, production of woody biofuels in New Zealand is projected to occur on marginal land, not where the most intense agriculture occurs (Todd *et al*., 2009). Falling costs and increasing efficiency of solar energy may limit future biofuel demand, given the limited efficiency of plants in converting solar energy into usable fuel (e.g. Reijnders and Huijbregts, 2007).

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25.9.2. Intra- and Inter-Regional Flow-On Effects Among Impacts, Adaptation and Mitigation

Recent studies strengthen conclusions from the AR4 (Hennessy *et al*., 2007) that flow-on effects from climate change impacts occurring in other world regions can exacerbate or counteract projected impacts in Australasia.

Modelling suggests Australia's terms of trade would deteriorate by about 0.23% in 2050 and 2.95% in 2100 as climate change impacts reduce economic activity and demand for coal, minerals and agricultural products in other world regions (A1FI scenario; Harman *et al*., 2008). As a result, Australian Gross National Product (GNP) is expected to decline more strongly than GDP due to climate change, especially towards the end of the 21st century (Gunasekera *et al*., 2008). These conclusions, however, merit only *medium confidence*, because they rely on simplified assumptions about global climate change impacts, economic effects and policy responses.

For New Zealand, there is *limited evidence* but *high agreement* that higher global food prices driven by adverse climate change impacts on global agriculture and some international climate policies would increase commodity prices and hence producer returns. Agriculture and forestry producer returns, for example, are estimated to increase by 14.6% under the A2 scenario by 2070 (Saunders *et al*., 2010) and real gross national disposable income by 0.6-2.3% under a range of non-mitigation scenarios (Stroombergen, 2010) relative to baseline projections in the absence of global climate change. Some climate policies such as biofuel targets and agricultural mitigation in other regions would also increase global commodity prices and hence returns to New Zealand farmers (Saunders *et al*., 2009; Reisinger *et al*., 2012). Depending on global implementation, these could more than offset projected average domestic climate change impacts on agriculture (Tait *et al*., 2008a). In contrast, higher international agricultural commodity prices appear insufficient to compensate for the more severe effects of climate change on agriculture in Australia (see 25.7.2; Gunasekera *et al*., 2007; Garnaut, 2008).

Climate change could affect international tourism to Australasia through international destination and activity preferences (Kulendran and Dwyer, 2010; Rosselló-Nadal *et al*., 2011; Scott *et al*., 2012), climate policies, and oil prices (Mayor and Tol, 2007; Becken, 2011; Schiff and Becken, 2011). These potentially significant effects remain poorly quantified, however, and are not well integrated into local vulnerability studies (Hopkins *et al*., 2012).

Climate change has the potential to change migration flows within Australasia, particularly due to coastal changes (e.g. from the Torres Straits islands to mainland Australia), although reliable estimates of such movements do not yet exist (see Chapter 12.4; Green *et al*., 2010b; McNamara *et al*., 2011; Hugo, 2012). Migration within countries, and from New Zealand to Australia, is largely economically driven and sustained by transnational networks, though the perceived more attractive current climate in Australia is reportedly a factor in migration from New Zealand (Goss and Lindquist, 2000; Green *et al*., 2008a; Poot, 2009). The impacts of climate change in the Pacific may contribute to an increase in the number of people seeking to move to nearby countries (Bedford and Bedford, 2010; Hugo, 2010; McAdam, 2010; Farbotko and Lazrus, 2012) and affect political stability and geopolitical rivalry within the Asia-Pacific region, although there is no clear evidence of this to date and causal theories are scarce (Dupont, 2008; Pearman, 2009; see Chapter 12.5). There is *high agreement* and *robust evidence* that increasing climate-driven disasters, disease and border control will stimulate operations other than war for Australasia's armed forces, and that integration of security into adaptation and development assistance for Pacific island countries can play a key role in moderating the influence of climate change on forced migration and conflict (Dupont and Pearman, 2006; Bergin and Townsend, 2007; Dupont, 2008; Sinclair, 2008; Barnett, 2009; Rolfe, 2009).

25.10. Synthesis and Regional Key Risks

25.10.1. Economy-wide Impacts and the Potential of Mitigation to Reduce Risks

Globally effective mitigation could reduce or delay some of the risks associated with climate change and make adaptation more feasible beyond about 2050, when projected climates begin to diverge substantially between mitigation and non-mitigation scenarios (see also 19.7). However, literature quantifying these benefits for Australasia is sparse. Economy-wide net costs for Australia are modelled to be substantially greater in 2100 under unmitigated climate change (A1FI; GNP loss 7.6%) than under globally effective mitigation (GNP loss less than 2% for stabilization at 450 or 550 ppm CO_2-eq, including residual impacts and costs of mitigation; Garnaut, 2008). These estimates, however, are highly uncertain and depend strongly on valuation of non-market impacts, treatment of potentially catastrophic outcomes, and specific assumptions about autonomous adaptation, global changes and flow-on effects for Australia, and effectiveness and implementation of global mitigation efforts (Garnaut, 2008). No integrated estimates of climate change costs across the entire economy exist for New Zealand.

The benefits of mitigation in terms of reduced risks have been quantified for some individual sectors in Australia, e.g. for irrigated agriculture in the Murray-Darling Basin (Quiggin *et al*., 2008; Quiggin *et al*., 2010; Valenzuela and Anderson, 2011; Scealy *et al*., 2012) and for net health outcomes (Bambrick *et al*., 2008). Although quantitative estimates from individual studies are highly assumption-dependent, multiple lines of evidence (see 25.7-8) give *very high confidence* that globally effective mitigation would significantly reduce many long-term risks from climate change to Australia. Benefits differ, however, between States for some issues, e.g. heat and cold mortality (Bambrick *et al*., 2008). Few studies consider mitigation benefits explicitly for New Zealand, but scenario-based studies give *high confidence* that mitigating emissions from a high (A2) to at least a medium-low (B1) emissions scenario would markedly lower the projected increase in flood risks (Ballinger *et al*., 2011; McMillan *et al*., 2012) and reduce risks to livestock production in the most drought prone regions (Tait *et al*., 2008a; Clark *et al*., 2011b). Mitigation would also reduce the projected benefits to production forestry, however, though amounts depend on the response to CO_2 fertilization (Kirschbaum *et al*., 2011a; 25.7.1).

25.10.2. Regional Key Risks as a Function of Mitigation and Adaptation

The Australia/New Zealand Chapter of the AR4 (Hennessy *et al*., 2007) concluded with an assessment of aggregated vulnerability for a range of sectors as a function of global average temperature. Building on recent additional insights, Table 25-8 shows eight key risks within those sectors that can be identified with *high confidence* for the 21st century, based on the multiple lines of evidence presented in the preceding sections and selected using the framework for identifying key risks set out in Chapter 19. This combines consideration of biophysical impacts, their likelihood, timing and persistence, with vulnerability of the affected system, based on exposure, magnitude of harm, significance of the system and its ability to cope with or adapt to projected biophysical changes. These key risks differ in the extent to which they can be managed through adaptation and mitigation, and some are more likely than others, but all warrant attention from a risk-management perspective.

[INSERT TABLE 25-8 HERE
Table 25-8: Key regional risks during the 21st century from climate change for Australia and New Zealand. Colour bars indicate risk as a function of global mean temperature relative to pre-industrial, based on the studies assessed and expert judgment, for the current (top bar) and a hypothetical fully adapted state (bottom bar). For each risk, relevant climate variables and trends are indicated by symbols, in approximate order of priority. Where relevant climate projections span a particularly wide range even for a given amount of global mean temperature change, risks are shown in two pairs for low and high end projections, each without and with effective adaptation.]

One set of risks comprises damages to natural ecosystems (significant change in coral reefs and decline of some montane and low-lying ecosystems) that can be moderated by globally effective mitigation but to which some damage now seems inevitable. For some species and ecosystems, there is *high confidence* that climatically

constrained ecological niches, fragmented habitats and limited adaptive movement collectively present hard limits to adaptation to further climate change (see also 25.10.3). A second set of key risks (increase in wild fire, heat waves, water scarcity and flood risk) comprises damages that could be severe but can be moderated or delayed by a portfolio of adaptation measures together with mitigation, and where the need for transformative adaptation increases with the rate and amount of climate change (see also 25.10.3). A third set of key risks (coastal damages from sea level rise, and loss of food production from severe drying) comprises potential impacts that are particularly uncertain within the 21st century, even for a given global temperature change, and where alternative scenarios for changes in other climate drivers materially affect levels of concern and adaptation needs. Even though scenarios of severe drying or rapid sea level rise have low or currently unknown probabilities, the associated impacts would so severely challenge adaptive capacity, including transformational changes, that they constitute important risks.

A first comparative assessment of exposure and damages from different hazards for Australia up to 2100 indicates that inland flooding will continue to be the most costly source of direct damages to infrastructure, even though the largest value of assets is exposed to bush fire. Exposure to and damages from coastal inundation are currently smaller, but would rise most rapidly beyond mid-century once sea level rise exceeds 0.5 m (Baynes *et al*., 2012).

An *emerging risk* is the compounding of extreme events, none of which would constitute a *key* risk in its own right, but that collectively and cumulatively across space, time and governance scales could stretch emergency response and recovery capacity and hamper regional economic development, including through impacts on insurance markets or multiple concurrent needs for major infrastructure upgrades (NDIR, 2011; Phelan, 2011; Baynes *et al*., 2012; Booth and Williams, 2012; Karoly and Boulter, 2013). Efforts are underway to better understand the potential importance of cumulative impacts and responses (CSIRO, 2011; Leonard *et al*., submitted) but evidence is as yet too limited to identify this as a *key risk* consistent with the definitions adopted in this report (see Chapter 19).

Climate change is projected to bring benefits to some sectors and parts of Australasia, at least under limited warming scenarios associated with globally effective mitigation (*high confidence*). Examples include an extended growing season for agriculture and forestry in cooler parts of New Zealand and Tasmania, reduced winter energy demand and illnesses in most of New Zealand and southern States of Australia, and increased winter hydropower potential in New Zealand's South Island (25.7.1, 25.7.2, 25.7.4, 25.8.1).

The literature supporting this assessment of key risks is uneven among sectors and between Australia and New Zealand; for the latter, conclusions in many sectors are based on limited studies that often use a narrow set of assumptions, models, and data and which, accordingly, have not explored the full range of potential outcomes.

25.10.3. Challenges to Adaptation in Managing Key Risks, and Limits to Adaptation

Two key and related challenges for regional adaptation are apparent: to identify when and where a move from incremental to transformative adaptation measures is needed; and, where specific interventions are needed to overcome adaptation constraints, in particular to support proactive and transformative responses that require coordination across different spheres of governance and decision-making (Palutikof *et al*., 2013). The magnitude of climate change, especially under scenarios of limited mitigation, and constraints to adaptation suggest that incremental and autonomous responses will not deliver the full range of adaptation options available, or to ensure natural and human systems can still function even if some key risks are realized (*high confidence*; see also 25.4).

Most incremental adaptation measures in natural ecosystems focus on reducing other non-climate stresses (25.6.1, 25.6.2) but, even with scaled-up efforts, conserving the current state and composition of natural ecosystems most at risk appears increasingly infeasible. Maintenance of key ecosystem functions and services and individual species requires a radical reassessment of conservation values and practices related to translocation of species and the values placed on "introduced" species (Steffen *et al*., 2009). Divergent views regarding intrinsic and service values of individual species and ecosystems imply that a proactive discussion is necessary to enable effective decision-making and resource allocation. In human systems, incremental adjustments of current tools, planning approaches and early warning systems for floods, fire, drought, water resources and coastal hazards will increase resilience to climate variability and could be sufficient under scenarios of limited climate change (*medium confidence*; Stafford-Smith,

2013). A purely incremental approach, however, which generally aims to preserve current management objectives, governance and institutional arrangements, creates a path-dependency that becomes increasingly constraining and costly to overcome once more transformative changes are needed (*high agreement, medium evidence*; e.g. Howden *et al.*, 2010; Park *et al.*, 2012; McDonald, 2013, and 25.4.2). Examples include: managed retreat from eroding coasts that are increasingly difficult or costly to protect; the transformation of some rural and remote communities; translocation of some industries and economic activities in response to increasing drought, flood and fire risks or water scarcity; and re-balancing protection from and accommodation or avoidance of flood risk (Boxes 25-1, -2, 5-9; Linnenluecke *et al.*, 2011; Kiem and Austin, 2012; O'Neill and Handmer, 2012; Fletcher *et al.*, submitted).

Consideration of transformative adaptation becomes critical where long life- or lead-times are involved, and where high up-front costs or multiple interdependent actors across a range of scales create barriers that require coordinated and proactive interventions (Stafford-Smith *et al.*, 2011b; Palutikof *et al.*, 2013). In these situations, deferring adaptation decisions due to limited knowledge about the future will not necessarily minimize costs or ensure adequate flexibility for future responses (Stewart and Wang, 2011; Gorrdard *et al.*, 2012; McDonald, 2013).

Nonetheless, thresholds and any need for policy support for transformative adaptation inevitably depend upon social, institutional and cultural values and objectives. Whether transformative responses are seen as success or failure of adaptation depends on the extent to which actors accept a change in, or wish to maintain current activities and management objectives, and the degree to which the values and institutions underpinning the transformation are shared or contested across stakeholders (Park *et al.*, 2012; Stafford-Smith, 2013). These views will differ not only between communities and industries but also from person to person depending on their individual value systems, perceptions of and attitude to risk, and ability to capitalize on opportunities (see also 25.4.3).

25.11. Filling Knowledge Gaps to Improve Management of Climate Risks

The wide range of projected rainfall changes (averages and extremes) and their hydrological amplification are key uncertainties affecting the scale and urgency of adaptation in agriculture, forestry, water resources, some ecosystems, and wildfire and flood risks. For ecosystems, agriculture and forestry, these uncertainties are compounded by limited knowledge of responses of vegetation to elevated CO_2, changes in ocean pH, and interactions with changing climatic conditions. The uncertainties in future impacts are most critical for decisions with long lifetimes, such as capital infrastructure investment or large-scale changes in land- and water-use. Uncertainties about the rate of sea level rise, and changes in storm paths and intensity, add to challenges for infrastructure design. The use of multi-model means and a narrow set of emissions scenarios in many past studies implies that the full set of climate-related risks and management options remains incompletely explored.

Understanding of ecological and physiological thresholds that, once exceeded, would result in rapid changes in species, ecosystems and their services, is still very limited. The literature is noticeably sparse in New Zealand and for arid Australia. These knowledge gaps are compounded by limited information about the effect of global climate change on patterns of natural climate variability, such as ENSO. Better understanding the effect of evolving natural climate variability and long-term trends on both invasive species and native and managed ecosystems could support more robust ecosystem-based adaptation strategies.

Vulnerability of human and managed systems depends critically on future socio-economic characteristics. Research into psychological, social and cultural dimensions of vulnerability, adaptive capacity and underpinning values remains limited and poorly integrated with bio-physical studies, which reduces confidence in conclusions regarding future vulnerabilities and the feasibility and effectiveness of adaptation strategies.

These multiple, persistent and structural uncertainties imply that, in most cases, adaptation requires an iterative risk management process. While decision-support frameworks are being developed, it remains unclear to what extent existing governance and institutional arrangements will be able to support more transformational responses, particularly where competing public and private interests and particularly vulnerable groups are involved. The enabling or constraining influences on adaptation from interactions among market forces, institutions, governance, policy and regulatory environments have only recently begun to attract research attention, mostly in Australia.

Climate change impacts, adaptation and mitigation responses in other world regions will affect Australasia, but our understanding of this remains very limited. Existing studies suggest transboundary effects, mediated mostly via trade but potentially also migration, can be of similar if not larger scale than direct domestic impacts of climate change for economically important sectors such as agriculture and tourism. However, scenarios used in such studies tend to be highly simplified. Effective management of risks and opportunities in these sectors would benefit from better integration of relevant global scenarios of climatic and socio-economic changes into studies of local impacts, vulnerabilities and adaptation options.

Frequently Asked Questions

FAQ 25-1: How can we adapt to climate change while projected future changes remain so uncertain?

A focus on distant impacts and their uncertainties can make adaptation to climate change appear an impossible task. However, a different approach can mitigate this perceived problem (Figure 25-6). First, many climate changes are reasonably certain, especially in the short to medium term (i.e. to mid-century). Examples include rising air and sea surface temperatures (including a related increase in heatwaves and moisture evaporation), rising atmospheric CO_2, increasing ocean acidification, and rising sea-levels. These changes are no more uncertain than other changes such as future population, economic development or exchange rates that also concern decision-makers.

Second, for adaptation, our attention should focus on decisions that can and will be made in the near future, on the 'lifetime' of those decisions, and the risk posed by climate change during that lifetime. Thus the choice of next year's annual crop, even though it is greatly affected by climate, only matters for a year or two and can be adjusted within a few years. When the adaptation challenge is reframed as implications for near-term decisions, many decisions are not greatly affected by climate change, or do not require a dedicated adaptation response. Third, there are, of course, decisions such as those about long-lived infrastructure and spatial planning which must take longer-term climate change into account, and in some cases these do need to be addressed in light of significant uncertainty. Even then, techniques exist and are widely used in other areas to reduce challenges for decision-making – including the precautionary principle, real options, adaptive management, no regrets strategies, or risk hedging. These can be matched to the type of uncertainty.

Last, adaptation is not a one-off action; change will be on-going and adaptation will take place along an evolving pathway, in which decisions are updated and revisited as the future unfolds and more information comes to hand (see Figure 25-6). While this creates an opportunity for learning, successive short-term decisions need to be monitored to avoid unwittingly creating an adaptation path that is not be sustainable as climate change continues, also referred to as maladaptation. Changing pathways (e.g. from a paradigm that favours protection from risks, to one that seeks to accommodate or avoid risks) can be challenging and may require new collaborations and interactions between decision-makers at various levels and the people affected by those decisions.

[INSERT FIGURE 25-6 HERE

Schematic illustration of adaptation as an iterative risk management process. Each individual adaptation decision comprises well known aspects of risk assessment and management (top left panel). Each such decision occurs within and exerts its own sphere of influence, determined by the lead- and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single correct adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations and goals.]

FAQ 25-2: Why and where does climate change matter to Australia and New Zealand?

Climate change will produce rises in temperatures, atmospheric CO_2 and sea levels as well as changes in rainfall and other precipitation patterns and some extreme weather events. Ecosystems have developed and many aspects of human society, including large-scale infrastructure, been designed to function under *current* climate conditions. The projected changes, accordingly, will affect water resources, coasts, infrastructure, agriculture, health and biodiversity in Australia and New Zealand.

For the range of plausible climate changes over the 21st century, key risks exist for Australia and New Zealand. These differ both in their likelihood and the degree to which they can be managed by adaptation and mitigation.

Some potential impacts, such as significant change in coral reef systems and loss of higher-altitude ecosystems, are very difficult to avoid entirely even if climate change is limited by mitigation. Some impacts, such as increased flood damage to settlements and infrastructures, increased health impacts, and infrastructure failure during heat waves, increasing water scarcity in some regions and increased damages to ecosystems and risk to human life, properties and infrastructure from wildfires, have the potential to be severe but can be moderated by effective mitigation combined with regional adaptation measures - although the degree and nature of adaptation required will depend on the amount of climate change. Other impacts are very uncertain but could arise even if global mitigation actions are effective. These include significant region-wide damages to coastal infrastructure and low-lying ecosystems from sea level rise, or a severe decline in water availability resulting in significant reduction in food production, e.g. in the Murray-Darling Basin. In spite of their uncertainty, the severe consequences of such extreme scenarios warrants their consideration in current risk management.

Cross-Chapter Box

Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use ($kWhr/m^3$) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of

water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.,* 2008, Bazilian *et al.,* 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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Table 25-1: Observed and projected changes in key climate variables, and (where assessed) the contribution of human activities to observed changes. For further relevant information see WGI Chapters 3, 6 (ocean changes, including acidification), 11, 12 (projections), 13 (sea level), and 14 (regional climate phenomena).

(*) *medium confidence*, (**) *high confidence*, (***) *very high confidence*, (****) *virtually certain*

Climate variable	***Observed change***	***Direction of projected change***	***Examples of projected magnitude of change*** *(relative to 1990, unless otherwise stated)*	***Additional comments***
Mean air temperature	***Aus:*** Increased by 0.09 ± 0.03°C per decade since 1911[1] (***) ***NZ:*** Increased by 0.09 ± 0.03°C per decade since 1909[2] (***)	***Aus and NZ:*** Increase [3-7](****); greatest over inland Aus and least in coastal areas and NZ[3, 4, 7, 8] (***)	***Aus:*** 0.5-1.5°C (2030 A1B), 1.0-2.5°C (2070 B1), 2.2-5.0°C (2070 A1FI)[5] ***NZ:*** 0.3-1.4°C (2040 A1B), 0.7-2.3°C (2090 B1), 1.6-5.1°C (2090 A1FI)[7] *CMIP5 RCP4.5, rel. to 1995[9]:* ***N Aus:*** 0.2-1.9°C (2035), 0.9-3.4°C (2065) ***S Aus & NZ:*** 0.1-1.2°C (2035), 0.6-2.2°C (2065)	***Aus:*** A significant contribution to observed change attributed to anthropogenic climate change[10] (**) with some regional variations attributed to atmospheric circulation variations[11, 12] ***NZ:*** Observed change partially attributed to anthropogenic climate change[13](*)
Sea surface temperature	***Aus:*** Increased by about 0.12°C per decade for NW&NE Aus and by about 0.2°C per decade for E Aus since 1950[14-16](***) ***NZ:*** Increased by about 0.07°C per decade from 1909-2009[2] (***)	**Aus and NZ:** Increase[3-5, 17](***) with greater increase in the Tasman sea region (*) [3-5, 17]	***Aus:*** 0.6-1.0°C (2070 B1) and 1.6-2.0°C (2070 A1FI) for southern coastal and 1.2-1.5°C (2070 B1) and 2.2-2.5°C (2070 A1FI) elsewhere[5] ***NZ:*** Similar to projected changes in mean air temperature for coastal waters[7, 18]	
Air temperature extremes	***Aus and NZ:*** Significant trend since 1950: cool extremes have become rarer and hot extremes more frequent and intense[19-22] (**)	***Aus and NZ:*** Hot days and nights more frequent and cold days and cold nights less frequent during the 21st century[5, 7, 18, 23-25](**)	***Aus:*** Hot days in Melbourne (>35°C max.) increase by 20-40% (2030 A1B), 30-90% (2070 B1) and 70-190% (2070 A1FI)[5] ***NZ:*** Spring and autumn frost-free land to increase by around 16% by 2080s; up to 60 more hot days (>25°C max.) for northern areas by 2090[7]	***Aus:*** Observed trend partly attributable to anthropogenic climate change[21-23, 26](**), although other factors may have contributed high extremes during droughts[27-29]
Precipitation	***Aus:*** Late autumn/winter decreases in SW Aus since the 1970s and in SE Aus since the mid 1990s, and annual increases in NW Aus since the 1950s[30-32](***) ***NZ:*** Mean annual rainfall increased over 1950-2004 in the south and west of both islands and decreased elsewhere[33] (***)	***Aus:*** Annual decline in SW Aus (**) and elsewhere in southern Aus (*) with the reductions strongest in the winter half year[5, 6, 34-36] (**). Direction of annual change elsewhere is uncertain[5, 36, 37] (Figure 25.2) (**) ***NZ:*** In the South Island, annual increase in the west and south and decrease in north-east. In the North Island, increase in the west and decrease in eastern and northern regions [7, 35, 38] (Figure 25.2) (**)	***Aus:*** For 2030 A1B, annual changes of-15% to +10% (N&E Aus) and -10% to 0% (S Aus), for 2070 B1, -15% to +7.5% (N&E Aus) and -15% to 0% (S Aus), and for 2070 A1FI, -30% to +20% (N&E Aus) and -30% to +5% (S Aus), with larger changes seasonally[5] ***NZ:*** For 2040 A1B, -5 to +15% (S&W) and -15% to +10% (N&E) and for 2090 A1B, -10% to +25% (S&W) and -20% to +15% (N&E) based on downscaled projections with larger changes seasonally[7, 38]	***Aus:*** Observed decline in SW is related to atmospheric circulation changes[39-41] (***), other factors[42], and partly attributable to anthropogenic climate change[41-44](***). The recent SE rainfall decline is also related to circulation changes[32, 45-47] (**), with some evidence of an anthropogenic component[48] ***NZ:*** Observed trends related to increased westerly winds[33]. Projected annual trends dominated by winter and spring trends related to increased westerlies[7]
Precipitation extremes	***Aus:*** Indices of annual daily extremes (e.g. 95th and 99th percentile rainfalls) show mixed or insignificant trends[23, 49], but significant increase is evident in recent decades for shorter duration (sub-daily) events[50, 51] (**). ***NZ:*** Extreme annual 1-day rainfall decrease in north and east and increase in west since 1930 (*).	***Aus and NZ:*** Increase in most regions in the intensity of rare daily rainfall extremes (i.e. current 20 year return period events) and in short duration (sub-daily) extremes (*) and an increase in the intensity of 99 percentile daily extremes (*low confidence*)[4, 7, 23, 52-56]	***Aus:*** For 2090 A2, CMIP3 give increases in the intensity of the 20 year daily extreme of +200% to -25% depending on region and model[53] ***NZ:*** Increases of daily extreme rainfalls of 8% per degree C are projected but with significant regional variations[7, 57]	***Aus and NZ:*** The sign of observed trends mostly reflects trends in mean rainfall (e.g. there is a decrease in mean and daily extremes in SW Aus)[23, 33, 50]. Similarly, future increases in intensity of extreme daily rainfall are more likely where mean rainfall is projected to increase[5]

Drought	***Aus:*** Defined using rainfall only, drought occurrence over the period 1900-2007 has not changed significantly[58](**) ***NZ:*** Defined using a soil water balance model, there has been no trend in drought occurrence since 1972[59] (*)	***Aus and NZ:*** Drought frequency is projected to increase in southern Australia [4, 55, 58, 60, 61](*) and in eastern and northern New Zealand[59, 62] (*)	***Aus:*** Occurrence under 2070 A1B ranges from a halving to 3 times more frequent in N. Aus, and 0-5 times more frequent in southern Aus[61] ***NZ:*** Time spent in drought in eastern and northern New Zealand is projected to double or triple by 2040[62]	***Aus:*** Regional warming may have led to an increase in hydrological drought (*low confidence*)[63, 64]
Winds	***Aus:*** Significant decline in storminess over SE Aus since 1885[65](*), but inconsistent trends in wind observations since 1975[66, 67] ***NZ:*** Mean westerly flow increased during the late 20th century (1978–1998), associated with the positive phase of the IPO[68, 69]	***Aus:*** Increases in winds in 20-30°S band, with little change to decrease elsewhere, except for winter increases over Tasmania. Decrease to little change in extremes (99th percentile) over most of Australia except Tasmania in winter[70] (*). ***NZ:*** Mean westerly winds and extreme winds (based on projected changes in circulation patterns) are projected to increase, especially in winter[7, 71](*)	***Aus:*** Magnitude of simulated changes are around 10% under A1B for 2081-2100 relative to 1981-2000[70] ***NZ:*** Westerlies to increase by approximately 10% by 2090[7]	***Aus and NZ:*** Many of past and projected changes in mean wind speed can be related to changes in atmospheric circulation[44, 68, 69] ***NZ:*** Extreme westerlies and southerlies have slightly increased while extreme easterlies have decreased since 1960[13, 72]
Mean sea level	***Aus:*** From 1920-2011 the average rate of relative sea level rise (SLR) was 1.6±0.1.4 mm/yr[73] (***) ***NZ:*** The average rate of relative SLR was 1.7±0.1 mm/yr over 1900-2009[74](***)	***Aus and NZ:*** Regional sea level rise will *very likely* exceed the 1971-2000 historical rate, consistent with global mean trends[75]. Mean sea level will continue to rise for at least several more centuries[75] (***).	***Aus and NZ:*** Off shore eastern Australian regional sea level rise, may exceed 10% more than global SLR, see AR5 WGI Chap13, Figure 13.15[75]	***Aus:*** Satellite estimates of regional SLR for 1993-2009 are significantly higher than those for 1920-2000, partly reflecting atmospheric circulation changes[73, 74, 76, 77] ***NZ:*** Allowing for glacial isostatic adjustment, absolute observed SLR is around 2.0mm/yr[74, 78]
Extreme sea level	***Aus:*** Extreme sea levels have risen at a similar rate to global SLR[79]	***Aus and NZ:*** Projected mean SLR will lead to large increases in the frequency of extreme sea level events (***), with changes in storm surges playing a lesser role[80-83]	***Aus:*** An increase of mean sea level by 0.1m increases the frequency of an extreme sea level event by a factor of between 5 and 10[80-82], depending on location	
Fire weather	***Aus:*** Increased since 1973(**) with 24 out of 38 sites showing increases in the 90th percentile of the McArthur Forest Fire Danger index[84]	***Aus:*** Fire weather is expected to increase in most of southern Australia due to hotter and drier conditions (**), based on explicit model studies carried out for SE Australia [85-88] , and change little or decrease in NE[88] (*) ***NZ:*** Fire danger is projected to increase in many areas[89](*)	***Aus:*** Very high and extreme fire danger increase 2-30% (2020), 10-100% (2050) (using B1 and A2 and two climate models, and 1973-2007 base)[85] ***NZ:*** Very high and extreme fire danger days increase 0 to 400% (2040), 0 to 600% (2090) (using A1B,16 CMIP3 GCMs)[89]	***Aus:*** For the example of Canberra, the projected changes represent the current 17 days per year increasing to 18-23 days in 2020 and 20-33 days in 2050[85]
Tropical cyclones and other severe storms	***Aus:*** No regional change in the number of tropical cyclones (TCs) or in the proportion of intense TCs over 1981-2007[90](*), but landfall in NE Aus has declined significantly since the 19th Century[91] and east-west distribution changed since 1980[92]	***Aus:*** Tropical cyclones are projected to increase in intensity, but stay similar or decrease in numbers[9, 93] (*low confidence*) ***NZ:*** Projected increase in the average intensity of cyclones in the south during winter, but a decrease elsewhere[71] (*)	***Aus:*** Modelling study shows a 50% reduction in TC occurrence for 2051-2090 relative to 1971-2000 but increases in intensity of the modelled storms[93] ***NZ:*** Occurrence of conditions conducive to convective storm development is projected to increase by 3–6% by 2070-2100 (A2), relative to 1970-2000, with the largest increases over the South Island[71]	***Aus:*** Single studies project decreased cool-season tornadoes in southern Australia[94], and hail increases in Sydney[95]
Snow and ice	***Aus:*** Late season significant snow depth decline at three out of four Snowy mountain sites over 1957-2002[96](**) ***NZ:*** Ice volume declined by almost 50% during the 20th century, with glacier volume reducing by at least 25% since 1950[97-100] (**).	***Aus:*** Both snow depth and area are projected to decline[96] (***) ***NZ:*** Snowline elevations are projected to rise, and winter snow volume and the duration of days with low elevation snow lying are projected to decrease[7, 101, 102] (**)	***Aus:*** Area with at least 30 days cover annually projected to decline 14-54% (2020) and 30-93% (2050) [96] ***NZ:*** By 2090, peak snow accumulation is projected to decline by 32-79% at 1000m and by 6-51% at 2000m[102]	***NZ:*** Atmospheric circulation variations can enhance or outweigh multi-decadal trends in ice volume over time scales of up to two decades[103, 104]

References: 1: Fawcett, *et al*. (2012); 2: Mullan, *et al*. (2010); 3: AR5-WGI-Ch11; 4: AR5-WGI-Ch12; 5: CSIRO and BoM (2007); 6: Moise and Hudson (2008); 7: MfE (2008); 8: AR5-WGI-Atlas; 9: AR5-WGI-Ch14; 10: Karoly and Braganza (2005); 11: Hendon, *et al*. (2007); 12: Nicholls, *et al*. (2010); 13: Dean and Stott (2009); 14: BoM (2011); 15: Lough (2008); 16: Lough and Hobday (2011); 17: AR5-WGI-Atlas-AI68-69; 18: Tait (2008); 19: Chambers and Griffiths (2008); 20: Gallant and Karoly (2010); 21: Nicholls and Collins (2006); 22: Trewin and Vermont (2010); 23: Alexander and Arblaster (2009); 24: Tryhorn and Risbey (2006); 25: Griffiths, *et al*. (2005); 26: Alexander, *et al*. (2007); 27: Deo, *et al*. (2009); 28: McAlpine, *et al*. (2007); 29: Cruz, *et al*. (2010); 30: Hope, *et al*. (2010); 31: Jones, *et al*. (2009); 32: Gallant, *et al*. (2012); 33: Griffiths (2007); 34: Timbal and Jones (2008); 35: AR5-WGI-Atlas-AI70-71; 36: Irving, *et al*. (in press); 37: Watterson (2012); 38: Reisinger, *et al*. (2010); 39: Bates, *et al*. (2008); 40: Frederiksen and Frederiksen (2007); 41: Hope, *et al*. (2006); 42: Timbal, *et al*. (2006); 43: Cai and Cowan (2006); 44: Frederiksen, *et al*. (2011); 45: Cai, *et al*. (2011); 46: Nicholls (2010); 47: Smith and Timbal (2010); 48: Timbal, *et al*. (2010a); 49: Gallant, *et al*. (2007); 50: Westra and Sisson (2011); 51: Jakob, *et al*. (2011); 52: Abbs and Rafter (2009); 53: Rafter and Abbs (2009); 54: Kharin, *et al*. (submitted); 55: IPCC-SREX-Chapter-3; 56: Westra, *et al*. (2013); 57: Carey-Smith, *et al*. (2010); 58: Hennessy, *et al*. (2008a); 59: Mullan, *et al*. (2005); 60: Kirono and Kent (2010); 61: Kirono, *et al*. (2011); 62: Clark, *et al*. (2011a); 63: Cai and Cowan (2008); 64: Nicholls (2006); 65: Alexander, *et al*. (2011); 66: McVicar, *et al*. (2008); 67: Troccoli, *et al*. (2012); 68: Parker, *et al*. (2007); 69: Mullan, *et al*. (2001); 70: McInnes, *et al*. (2011a); 71: Mullan, *et al*. (2011); 72: Salinger, *et al*. (2005); 73: Burgette, *et al*. (submitted); 74: Hannah and Bell (2012); 75: AR5-WGI-Ch13; 76: CSIRO and BoM (2012); 77: Meyssignac and Cazenave (2012); 78: Hannah (2004); 79: Menendez and Woodworth (2010); 80: McInnes, *et al*. (2009); 81: McInnes, *et al*. (2011); 82: McInnes, *et al*. (2012); 83: Harper, *et al*. (2009); 84: Clarke, *et al*. (2012); 85: Lucas, *et al*. (2007); 86: Hasson, *et al*. (2009); 87: Cai, *et al*. (2009a); 88: Clarke, *et al*. (2011); 89: Pearce, *et al*. (2011); 90: Kuleshov, *et al*. (2010); 91: Callaghan and Power (2011); 92: Hassim and Walsh (2008); 93: Abbs (2012); 94: Timbal, *et al*. (2010b); 95: Leslie, *et al*. (2008); 96: Hennessy, *et al*. (2008); 97: Anderson, *et al*. (2006a); 98: Anderson and Mackintosh (2006); 99: Chinn, *et al*. (2012); 100: Clare, *et al*. (2002); 101: Fitzharris (2004); 102: Hendrikx, *et al*. (2012); 103: Purdie, *et al*. (2011); 104: Willsman, *et al*. (2010)

Table 25-2: Constraints and enabling factors for institutional adaptation processes in Australasia.*

Constraint	Enabling factors	References
Uncertainty of projections	Improved guidance and tools to manage uncertainty and support adaptive management Increased focus on lead and consequence time of decisions and link with current climate variability Increased communication between practitioners and scientists to identify and provide decision-relevant data	(Reisinger *et al.*, 2011; Stafford-Smith *et al.*, 2011b; Johnston *et al.*, 2012; Murta *et al.*, 2012; Park *et al.*, 2012; Productivity Commission, 2012; Randall *et al.*, 2012; Verdon-Kidd *et al.*, 2012; Stafford-Smith, 2013; Webb *et al.*, submitted)
Availability and cost of data and models	Central provision of relevant core climate and non-climate data, including regional scenarios projected changes National first-pass risk assessments	(DCC, 2009; Smith *et al.*, 2010; DCCEE, 2011; Baynes *et al.*, 2012; Roiko *et al.*, 2012; Mukheibir *et al.*, 2013; Webb and Beh, 2013; Lawrence *et al.*, submitted-b)
Limited financial and human capability and capacity; time lag in developing expertise	Support for pilot projects Building capacity through institutional commitment and learning Central databases on guidance, tools, methodologies, case studies Regional partnerships and collaborations, knowledge networks	(Smith *et al.*, 2008; Gardner *et al.*, 2010; Preston and Kay, 2010; DSEWPC, 2011; Johnston *et al.*, 2012; Low Choy *et al.*, 2012; Murta *et al.*, 2012; Park *et al.*, 2012; Yuen *et al.*, 2012; Webb and Beh, 2013; Lawrence *et al.*, submitted-b; Mustelin *et al.*, submitted; Webb *et al.*, submitted)
Unclear problem definition and goals; unclear standards for choices in risk assessment methodologies and decision support tools; limited monitoring and evaluation	Explicit but iterative framing and scoping of adaptation challenge, to reflect alternative entry points for stakeholders while meeting expectations of project sponsors to ensure long-term support Tailoring decision-making frameworks to specific problems Criteria and tools to monitor and evaluate adaptation success	(Nelson *et al.*, 2008; Preston *et al.*, 2008; Preston and Stafford-Smith, 2009; Rouse and Norton, 2010; Britton *et al.*, 2011; Maru *et al.*, 2011; Fünfgeld *et al.*, 2012; Randall *et al.*, 2012; Verdon-Kidd *et al.*, 2012; Mukheibir *et al.*, 2013; Webb and Beh, 2013; Webb *et al.*, submitted)
Unclear or contradictory legislative frameworks and responsibilities, unclear liabilities	Clear and coordinated legislative frameworks Defined responsibilities for public and private actors, including liabilities from acting and failure to act Legally binding guidance on the incorporation of climate change in planning mechanisms	(Smith *et al.*, 2008; Norman, 2009; Parliament of Australia, 2009; McDonald, 2010; Minister of Conservation, 2010; Rouse and Norton, 2010; Abel *et al.*, 2011; McDonald, 2011; Rive and Weeks, 2011; Corkhill, 2013; McDonald, 2013; Lawrence *et al.*, submitted-b)
Static planning mechanisms and practice; competing mandates and fragmentation of policies; disciplinary voids or single approaches	Whole-of-council approach to climate adaptation Long-term policy commitments and implementation support Increased policy coherence across sectors Strengthening multi-disciplinarity across professional fields	(Smith *et al.*, 2008; CSIRO, 2011; Measham *et al.*, 2011; Preston *et al.*, 2011; Reisinger *et al.*, 2011; Rive and Weeks, 2011; Webb and Beh, 2013; Lawrence *et al.*, submitted-b; Mustelin *et al.*, submitted)
Lack of political leadership; short election cycles; limited community support, participation and awareness for adaptation	Legally binding guidance and clarification of liabilities and duty of care to reduce dependence on individual leadership Consistent communication of current and potential future vulnerability and implications for community values Comprehensible communication of and access to response options, and their consistency with wider development plans Clearly identified entry points for public participation	(Smith *et al.*, 2008; Gardner *et al.*, 2009a; Britton *et al.*, 2011; Hobson and Niemeyer, 2011; Rouse and Blackett, 2011; Alexander *et al.*, 2012; Burton and Mustelin, 2013; Keys *et al.*, 2013)

* Note: The relevance of each constraint varies among organisations, sectors and location. Some enabling factors are only beginning to be implemented or have only been suggested in the literature, hence their effectiveness cannot yet be evaluated. Entries exclude issue-specific responses, such as early warning systems and their funding and operation, or funding mechanisms for capital infrastructure upgrades or retreat schemes.

Table 25-3: Examples of detected changes in species, natural and managed ecosystems, consistent with a climate change[1] signal, published since the AR4. Confidence in detection of change is based on the length of study, and the type, amount and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate being a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change.

Type of change and nature of evidence	Examples	Time scale of observations	Confidence in the detection of biological change	Potential climate change driver(s) [1]	Confidence in the role of climate vs other drivers
Morphology *Limited evidence* (1 study)	Declining body size of southeast Australian passerine birds, equivalent to ~7º latitudinal shift (Gardner *et al*., 2009b)	~100 years	***medium*** trend significant for 4 out of 8 species, two other species show same trend but not statistically significant	Warming air temperatures ~1.0ºC over same period	***medium*** Nutritional cause discounted
Geographic distribution *High agreement, robust evidence* for many marine species & mobile terrestrial species	Southerly range extension of the barrens-forming sea urchin *Centrostephanus rodgersii* from the NSW coast to Tasmania; flow on impacts to marine communities including lobster fishery; shift of 160 km per decade over 30 years (Ling, 2008; Ling *et al*., 2008), (Ling *et al*., 2009; Banks *et al*., 2010)	~30-50 years (first recorded in Tasmania late 1970s)	***high***	Increased sea surface temperature (SST), Ocean warming in SE Australia, increased southerly penetration of the East Australian Current (EAC), 350 km over 60 years	***high***
	Forty-five fish species, representing 27 families (about 30% of the inshore fish families occurring in the region), exhibited major distributional shifts in Tasmania (Last et al 2011)	distributions from late 1880s, 1980s and present (1995-now)	***high***	Increased SST SE Australia, increased southerly penetration of EAC	***medium*** Changed fishing practices have potentially contributed to trends
	Southward range shift of intertidal species (average minimum distance 116 km) off west coast of Tasmania; 55% species recorded at more southerly sites, only 3% species expanded to more northerly sites (Pitt *et al*., 2010)	~50 years Sites resampled 2007-2008, compared with 1950s	***medium***	Increased SST in SE Australia (average 0.22ºC per decade), increased southerly penetration of the EAC, 350 km over 60 years	***medium***
Life cycles *Robust evidence, medium agreement*; increasing documentation of	Significant advance in mean emergence date of 1.5 days per decade (1941-2005) in the Common Brown butterfly *Heteronympha merope* in Australia (Kearney *et al*., 2010a)	65 years	***high***	Increase in local air temperatures of 0.16ºC per decade (1945-2007)	***high*** Advance consistent with physiologically based model of temperature influence on development

advances in phenology in some species (mainly migration and reproduction in birds, emergence in butterflies, flowering in plants) but also significant trends towards later life cycle events in some taxa	Earlier wine-grape ripening at 9 of 10 sites in Australia (Webb *et al*. 2012)	Multiple time periods up to 64 years (average 41 years)	***high***	Increased length of growing season, increased average temperature and reduced soil moisture	***medium*** Changed husbandry techniques, resulting in lower crop yields, may have contributed to trend
	Timing of migration of glass eels, *Anguilla* spp. advanced by several weeks in Waikato River, North island, New Zealand (Jellyman *et al*., 2009)	30 years (2004-2005 compared to 1970s)	***medium***	Warming water temperatures in spawning grounds	***low*** Changes in discharge discounted as contributing factor
Marine productivity *Limited evidence, medium agreement*	Otolith ("ear stone") analyses in long-lived Pacific fish indicates significantly increased growth rates for shallow-water species (<250 m) (3 of 3 species), reduced growth rates of deep-water (>1000 m) species (3 of 3 species); no change observed in the 2 intermediate-depth species (Thresher *et al*., 2007)	Birth years ranged 1861-1993 (fish 2-128 years old)	***high***	Increasing growth rates in species in top 250m associated with warming SST, declining growth rates in species >1000m associated with long-term cooling (as indicated by Mg/Ca ratios and delta^{18}O in deep water corals)	***medium*** Changed fishing pressure may have contributed to trend
	~50% decline in growth rate and biomass of spring phytoplankton bloom in western Tasman Sea (Thompson *et al*., 2009)	60 years (1997-2007)	***high***	Increased SST and extension EAC associated with reduced nutrient availability	***medium***
Vegetation change *Limited agreement & evidence*; interacting impacts of changed land practices, altered fire regimes, increasing atmospheric CO_2 concentration and climate trends difficult to disentangle	Expansion of monsoon rainforest at expense of eucalypt savanna and grassland in Northern Territory, Australia (Banfai and Bowman, 2007) (Bowman *et al*., 2010)	~40 years	***medium***	Increases in rainfall and atmospheric CO_2	***medium*** Changes in fire regimes and land management practices may have contributed to trend
	Net increase in mire wetland extent (10.2%) and corresponding contraction of adjacent eucalypt woodland in seven sub-catchments in south east Australia (Keith *et al*., 2010)	Weather data covers 40 years; vegetation mapping from 1961-1998	***medium***	Decline in evapo-transpiration	***low*** Resource exploitation, fire history and autogenic mire development discounted

Freshwater communities *Limited evidence* (1 study)	Decline in families of macroinvertebrates that favour cooler, faster-flowing habitats in NSW streams and increase in families favouring warmer and more lentic conditions (Chessman, 2009)	13 years (1994-2007)	***medium***	Increasing water temperatures and declining flows	***low*** Variation in sampling, changes in water quality, impacts of impoundment and water extraction may have contributed to trends
Disease *Limited evidence, robust agreement*	Emergence and increased incidence of coral diseases including white syndrome (since 1998), and black band disease (since 1993-4) (Bruno *et al.*, 2007), (Sato *et al.*, 2009), (Dalton *et al.*, 2010)	1998 onwards	***medium***	Increasing SST	***high***
Coral reefs *Robust evidence & high agreement*	Multiple mass bleaching events since 1979 (see 25.6.2, 30.5)	1979 onwards	***high***	Increasing SST	***high***
	Calcification of *Porites* on GBR declined 21% (1971-2003) (n=4 reefs); (Cooper *et al.*, 2008), 14.2% (1990-2005) (n=69 reefs) (De'ath *et al.*, 2009)	1971-2003; 1961-2005	***high***	Increasing SST	***high*** Changes in water quality discounted

Table 25-4: Examples of potential consequences of climate change for invasive and pathogenic species relevant to Australia and New Zealand, with consequence categories based on Hellman et al. (2008).

Consequence	Projected	Organism/Ecosystem affected	Reference
altered mechanisms of transport and introduction	Increased risk of introduction of Asiatic Citrus Psyllid, (*Diaphorina citri*), vector of the disease huanglongbing	Australian citrus industry and native citrus and other rutaceaous species and endemic psyllid fauna	(Finlay *et al.*, 2009)
altered distribution of existing invasive & pathogenic species	*Nassella neesiana* (Chilean needle grass): increased droughts favour establishment	Managed pasture in New Zealand	(Bourdôt *et al.*, 2012)
	Warming and drying may encourage the spread of existing invasives such as *Pheidole megacephala* and provide suitable conditions for other exotic ant species if they invade	Human health and potentially agricultural and natural ecosystems	(Harris and Barker, 2007)
	Reduced climatic suitability for exotic invasive grasses in Australia (11 species including *Nassella* sp.)	Australian rangeland	(Gallagher *et al.*, 2012)
	Range of the invasive weed *Lantana camara* (lantana) projected to extend from Northern Australia to Victoria, South Australia and Tasmania.	Multiple	(Taylor *et al.*, 2012b)
	Projected increases in the range of three recently naturalised sub-tropical plants (*Archontophoenix cunninghamiana*, *Psidium guajava*, *Schefflera actinophylla*)	Native ecosystems in New Zealand	(Sheppard, 2012)
altered climatic constraints on invasive & pathogenic species	Queensland fruit fly (*Bactrocera tryoni*) moving southwards	Horticulture	(Sutherst *et al.*, 2000)
	Significant association between amphibian declines in upland rainforests of North QLD and three consecutive years of warm weather suggests future warming could increase the vulnerability of frogs to chytridiomycosis caused by the chytrid fungus *Batrachochytrium dendrobatadis*	Native frogs	(Laurance, 2008)
altered impact of existing invasive & pathogenic species	*Fusarium pseudograminearum* causing crown rot increases under elevated CO_2	Wheat	(Melloy *et al.*, 2010)
	Increased abundance of the root-feeding nematode *Longidorus elongatus* under elevated CO_2	New Zealand pasture	(Yeates and Newton, 2009)
	Increased severity of Swiss needle cast disease caused by *Phaeocryptopus gaeumannii*	Douglas fir plantations in New Zealand, impact more severe in North Island	(Watt *et al.*, 2011b)
altered effectiveness of management strategies	Light brown apple moth, *Epiphyas postvittana* (Walker) (Lepidoptera:Tortricidae) reduction in natural enemies due to asynchrony and loss of host species	Australian horticulture	(Thomson *et al.*, 2010)
	Projected changes in the efficacy of five biological control systems demonstrating a range of potential disruption mechanisms	Pastoral and horticultural systems in New Zealand	(Gerard *et al.*, 2012)

Table 25-5: Examples of co-beneficial climate change adaptation options for urban areas and barriers to their adoption. Options in italics are already widely implemented in Australia and New Zealand urban areas.

Climate impact	**Adaptation options**	**Co-benefits**	**Barriers to adoption**	**References**
Hot days and heatwaves	Greening cities/roofs; *more green spaces*; well-designed energy efficient buildings; occupant behavioural change; standards for new and retrofitting of existing infrastructure and assets	Energy efficiency; reduced risk of blackouts; fewer health impacts; resilient infrastructure and assets	Lack of standards; high installation costs; limited understanding of benefits; high individual discount rate; split of private costs and public benefits	(BRANZ, 2007; Coutts *et al.*, 2010; Stephenson *et al.*, 2010; Williams *et al.*, 2010; Tables 25-5, 25-6; Moon and Han, 2011; Ren *et al.*, 2012)
Decreased water supply and drought	Supply augmentation (*water recycling*, *rainwater harvesting*, *increased storage*, desalinisation); *demand management*; *infrastructure upgrades*; *integrated urban sensitive design*	Water self-sufficiency for current and future demand/population; less pipe/storage leakage; reduced environmental impacts from abstraction	Potential health impacts of recycled water; lower than expected uptake of demand options and relaxation after crises; trade-offs between supply and demand management	See Box 25-2 for more detail; also Table 25-5
River and local flooding, coastal erosion and inundation	*Building and infrastructure (e.g. drainage) improvements*; *upgrades of protection systems*; buffers from hazard-prone areas; *raising minimum floor levels*; rezoning/ relocation; integrated urban sensitive design	Reduced damages to homes and infrastructure and loss of life; decreased insurance premiums	High implementation cost especially if retrospective on existing stock; rezoning/ relocation can affect property prices and are highly contested	See Boxes 25-1 and 25-8 for more detail
Severe storms and tropical cyclones	New building design to withstand higher wind pressures; rezoning/relocation	Reduced damages to homes and infrastructure and loss of life; decreased insurance premiums	High implementation cost; rezoning/ relocation can affect property prices and are highly contested	(Mason and Haynes, 2010; Wang *et al.*, 2010b; Stewart and Wang, 2011; Mason *et al.*, 2013)
Corrosion from increased atmospheric CO_2 levels	Improved standards for construction using concrete; application of coatings for existing building stock	Reduced rates of carbonation-induced corrosion of concrete	Effectiveness of coatings varies with age and condition of concrete	(Stewart *et al.*, 2012; Wang *et al.*, 2012)

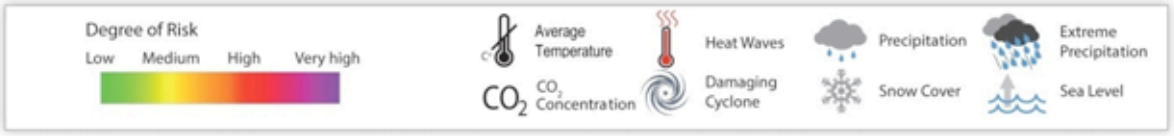
Table 25-6: Examples of interactions between impacts and adaptation measures in different sectors. In each case, impacts or responses in one sector have the potential to conflict (cause negative impacts) or be synergistic (have co-benefits) with impacts or responses in another sector, or with another type of response in the same sector.

Primary goal	Sector(s) affected	Examples of interactions between impacts and adaptation responses
Reduction of bushfire risk in natural landscapes	Biodiversity, tourism	Potential for greater conflict between conservation managers and other park users in Kosciuszko National Park if increasing fire incidence causes park closures, either to reduce risk, or to rehabilitate vegetation after fires (Wyborn, 2009), e.g. Objectives of the Wildfire Management Overlay (WMO) in Victoria conflicts with vegetation conservation (Hughes and Mercer, 2009).
Reduction of risk to energy transmission from bushfires	Biodiversity, energy	Underground cabling would reduce both the susceptibility of transmission networks to fire and ignition sources for wild fires, thus reducing risks to ecosystems and settlements; constraints include significant investment cost, diverse ownership of assets and lack of an overarching national strategy (ATSE, 2008; Parsons Brinkerhoff, 2009; Linnenluecke *et al.*, 2011).
Protection of coastal infrastructure	Biodiversity, tourism	Seawalls may provide habitat but these communities have different diversity and structure to those developing on natural substrates (Jackson *et al.*, 2008); groynes potentially alter beach fauna diversity and community structure (Walker *et al.*, 2008); continuing hard protection against sea level rise results in long-term loss of coastal amenities (Gorrdard *et al.*, 2012).
Avoidance of risks from sea level rise via relocation	Indigenous communities	Relocation can avoid increasing local pressures on communities from sea level rise but raises complex cultural, land rights, legal and economic issues, e.g. potential relocation of Torres Strait islander communities (Green *et al.*, 2010b; McNamara *et al.*, 2011).
Allocating scarce water resources via market instruments	Rural areas, agriculture, mining	Market based instruments such as water trading help allocation of scarce water resources to the highest value uses. The negative implications of this include potential loss of access to lower value users, which in some areas includes agriculture and drinking water supplies, with potentially significant social, environmental and wider economic consequences (Kiem and Austin, 2012).
Increased water security via water storage and irrigation for urban and agricultural systems	Biodiversity, water demand management	Water storage can buffer urban settlements and agricultural systems via irrigation against low runoff and high variability in river flow. Altered flow regimes have significant negative impacts on freshwater ecosystems (Bond *et al.*, 2008; Pittock *et al.*, 2008; Kingsford, 2011). Discharge from desalination plants (e.g. in Perth and Sydney) can lead to substantial local increases in salinity and temperature, and the accumulation of metals, hydrocarbons and toxic anti-fouling compounds in receiving waters (Roberts *et al.*, 2010) and reduce the effectiveness of measures to reduce water demand (Barnett and O'Neill, 2010).

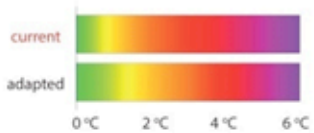
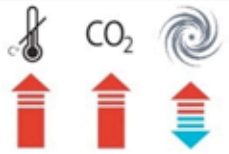
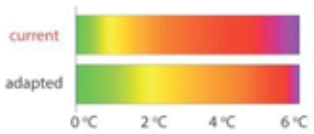
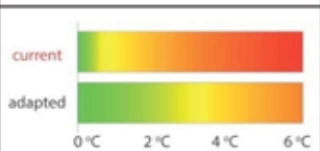
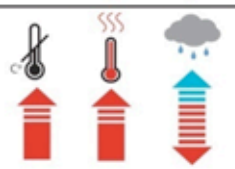
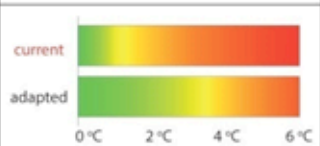
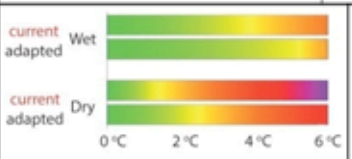
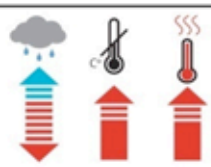
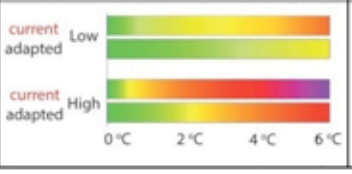
Table 25-7: Examples of interactions between adaptation and mitigation measures (green rows denote synergies where multiple benefits may be realized, orange rows denote potential tradeoffs and conflicts; grey row gives an example of complex, mixed interactions). The primary goal may be adaptation or mitigation.

Primary goal	Sector(s) affected	Examples of interactions between adaptation and mitigation responses
Adaptation to decreasing snowfall	Biodiversity, energy use, water use	Snowmaking in the Australian Alps would require large additional energy and water resources by 2020 of 2500-3300 ML of water per month, more than half the average monthly water consumption by Canberra in 2004-05. Increased snowmaking negatively affects vegetation, soils and hydrology of subalpine-alpine areas (Pickering and Buckley, 2010; Morrison and Pickering, 2011; ABS, 2012c).
Air conditioning for heat stress	Health, energy use	Rising temperatures degrade building energy efficiency (Wang *et al*., 2010a) and increase energy demand and associated CO_2 emissions if summer cooling needs are met by increased air conditioning (Stroombergen *et al*., 2006; Thatcher, 2007; Wang *et al*., 2010a).
Renewable wind energy production	Biodiversity	Wind-farms can have localised negative effects on bats and birds. However, risk assessment of the potential negative impacts of wind turbines on threatened bird species in Australia indicated low to negligible impacts on all species modelled (Smales, 2006).
Urban densification	Biodiversity, water, health	Higher urban density to reduce energy consumption from transport and infrastructure can result in loss of permeable surfaces and tree cover, intensify flood risks, and exacerbate discomfort and health impacts of hotter summers (Hamin and Gurran, 2009).
Water supply from desalination	Energy demand	Meeting increasing urban water demand via desalination plants increases energy demand and CO_2 emissions if this demand is met by increased fossil fuel energy generation (Barnett and O'Neill, 2010; Stamatov and Stamatov, 2010).
Secure food production in a warming climate	Nitrous oxide and methane emissions	Net greenhouse gas emissions intensity from dairy systems in southern Australia have been estimated to increase in future in several locations due to a changing climate and management responses (Cullen and Eckard, 2011; Eckard and Cullen, 2011). A shift towards perennial C4 grasses would increase methane emissions from grazing ruminants due to lower feed quality, but studies in south-west Australia suggest this could be more than offset by increased soil carbon storage (Thomas *et al*., 2012; Bradshaw *et al*., submitted).
Housing design to reduce peak energy demand	Energy use, infrastructure, health	Reducing peak energy demand through building design and demand management reduces vulnerability of electricity networks and transmission losses during heat waves (Parsons Brinkerhoff, 2009; Nguyen *et al*., 2010), reduces heat stress during summer and provides health benefits during winter (Strengers, 2008; Howden-Chapman, 2010; Strengers and Maller, 2011; Ren *et al*., 2012).
Energy from second-generation biofuels	Biodiversity, rural areas, agriculture	New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services including reducing erosion (Cocklin and Dibden, 2009; Giltrap *et al*., 2009; McHenry, 2009).
Reduction of emissions from fires	Biodiversity, livelihoods	Improved management of savanna fires to reduce the extent of high intensity late season fires could substantially reduce emissions as well as having significant benefits for biodiversity and indigenous employment (Russell-Smith *et al*., 2009; Bradshaw *et al*., submitted).
Reduce methane emissions from feral camels	Biodiversity, agriculture	Feral camels in Australia are projected to double from 1 to 2 million by 2020. Control of exotic vertebrate pests to reduce methane emissions could have significant biodiversity benefits (NRMMC, 2010; Bradshaw *et al*., submitted). Economic benefits of reduced grazing competition, infrastructure damage and greenhouse gases could outweigh costs of camel reductions (Drucker *et al*., 2010).

Table 25-8 | Key regional risks during the 21st century from climate change for Australia and New Zealand. Colour bars indicate risk as a function of global mean temperature relative to pre-industrial, based on the studies assessed and expert judgement, for the current (top bar) and a hypothetical fully adapted state (bottom bar). For each risk, relevant climate variables and trends are indicated by symbols, in approximate order of priority. Where relevant climate projections span a particularly wide range even for a given amount of global mean temperature change, risks are shown in two pairs for high and low end projections, each without and with effective adaptation*.



Arrows show projected future changes in key drivers under a range of climate and mitigation scenarios. Arrows pointing in both directions indicate that the direction of change (indicated by red and blue colours) is uncertain. Narrow horizontal bars indicate the range of potential changes, with more bars indicating greater uncertainty. Thick bars are used where the direction of change is highly certain and some amount of further change over the 21st century is virtually unavoidable even under mitigation scenarios.

Key Regional Risk		Risk for current and hypothetical fully adapted state	Key Climate Drivers and Trends	Key adaptation issues / prospects
Impacts that can be delayed but now appear very difficult to avoid entirely, even with globally effective mitigation and proactive adaptation	Significant change in community structure of coral reef systems in Australia [25.6.2, 30.5, Box CC-CR]			Limited evidence for autonomous genetic adaptation of corals; other adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing
	Loss of montane eco-systems and some endemic species in Australia [25.6.1]			Direct adaptation options are limited, but reducing other stresses such as pests, diseases and predator control and enhancing connectivity of habitats provides immediate co-benefits; need to consider translocation and migration
Impacts that have the potential to be severe but can be moderated or delayed significantly by globally effective mitigation and a portfolio of available adaptation measures	Wild fire damages to ecosystems and settlements and risks to human life in southern Australia and many parts of New Zealand [Table 25-1, Box 25-6]			Part of integrated landscape management; trade-offs exist between different management objectives and settlement patterns and goals
	Systematic constraints on water resource use in southern Australia [25.5.1, Box 25-2, 25-9]			Water resources already struggling to meet unlimited demand in many locations and exacerbated by projected population growth; effective adaptation relies on combination of demand and supply mechanisms
	Increase in morbidity and mortality and infrastructure failure during heat waves in Australia [25.7.4, 25.8.1]			Linked to social dynamics and ageing population in cities; transport and power infrastructure already at coping limit in many regions, with significant financial costs from future upgrades
	Increased frequency and intensity of flood damage to infrastruc-ture and settlements in Australia and New Zealand [25.2, Table 25-1, Box 25-8, 25-9]			Significant adaptation deficit in some regions to current flood risk; effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility
Impacts that have a low or currently unknown probability but cannot be ruled out even with globally effective mitigation, and would present major challenges if realized	Significant reduction in food production in the Murray-Darling Basin, far south-east Australia and eastern and northern parts of New Zealand [25.2, Table 25-1, 25.6.1, 25.7.2, Box 25-2, 25-5]			Immediate co-benefits from improved management of over-allocated water resources and balancing competing demands, but the extreme dry end would threaten agricultural production as well as ecosystems and some rural communities
	Widespread damages to coastal infrastructure and low-lying ecosys-tems in Australia and New Zealand [Table 25-1, 25.6.1, 25.6.2, Box 25-2, 25-9]			Adaptation deficit in some locations to current coastal erosion and flood risk; successive building and protection cycles constrain flexible responses; effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation

* For rainfall and its impact on food production, wet and dry scenarios represent approximately the 10 and 90 percentile range of current model projections and RCP emissions scenarios. For sea level, the low scenario is a 0.39 m rise by 2100 (mid-range model projections, RCP 2.6); the high scenario is a 1.5 m rise by 2100 (semi-empirical models, RCP 8.5). See AR5 WGI Chap 13 for more details. Under either scenario, sea level would continue to rise beyond 2100, but the focus of the risk assessment here is for risks that could be realised during the 21st century.

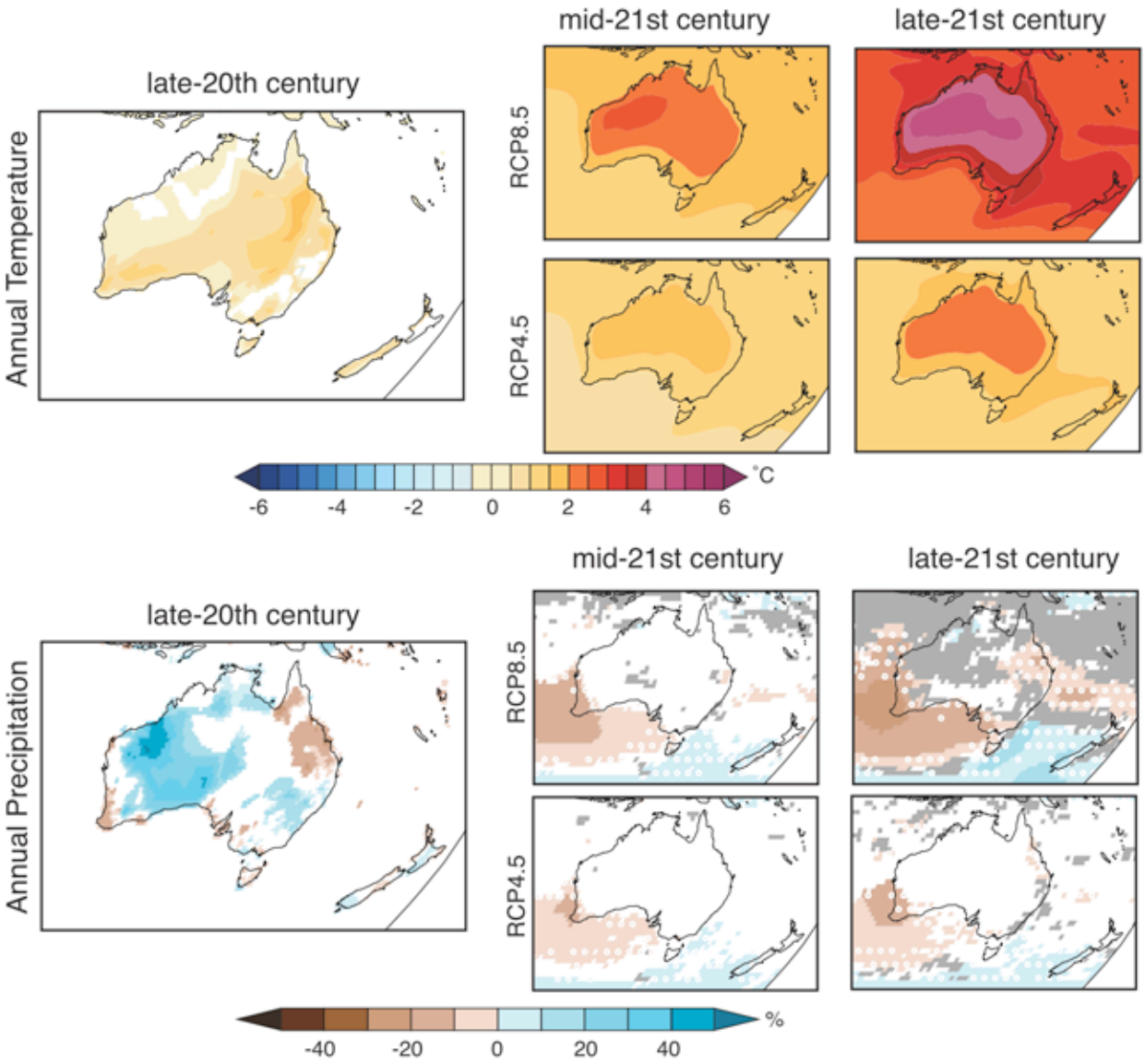


Figure 25-1: Observed and projected change in annual temperature and precipitation.

Maps: Change in annual temperature and precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

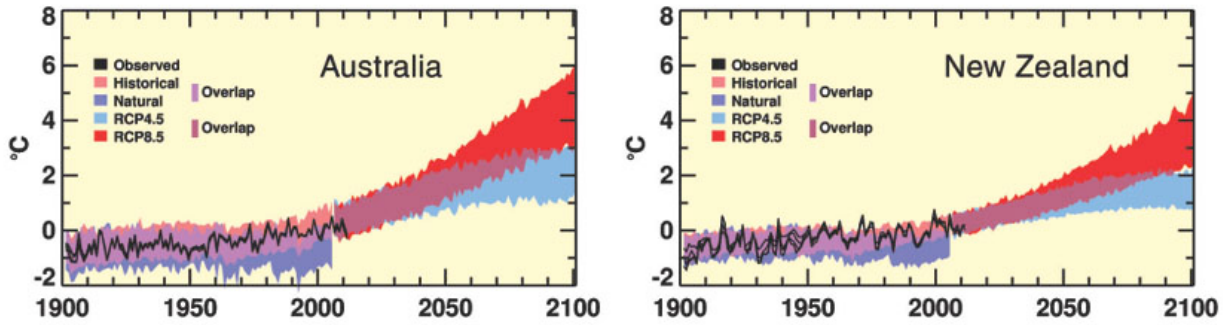


Figure 25-2: Observed and simulated variations in past and projected future annual average temperature over land areas of Australia (left) and New Zealand (right). Black lines show several estimates from measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Chapter 21.

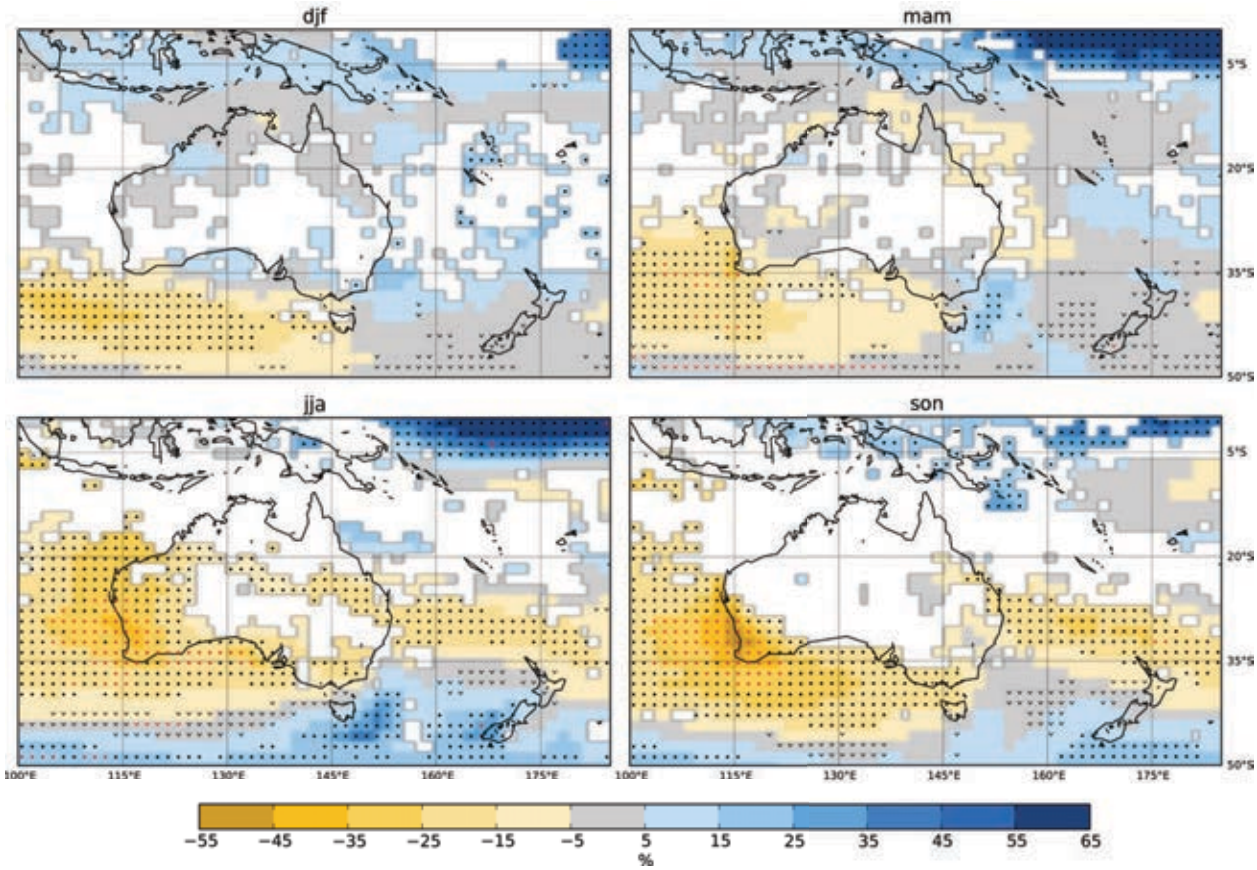


Figure 25-3: Projected CMIP5 multi-model mean change in rainfall for 2080-2099 relative to 1980-1999, under RCP 8.5. Dots [carets] indicate where the models agree (>90% red; >67% black) that there will [will not] be a substantial increase (>10%) or decrease (< -10%). White areas indicate where the models agree (> 67%) that there will be a substantial change in rainfall (larger in magnitude than 10%) however <67% agree on the direction of this substantial change (Figure from Irving *et al.*, in press).

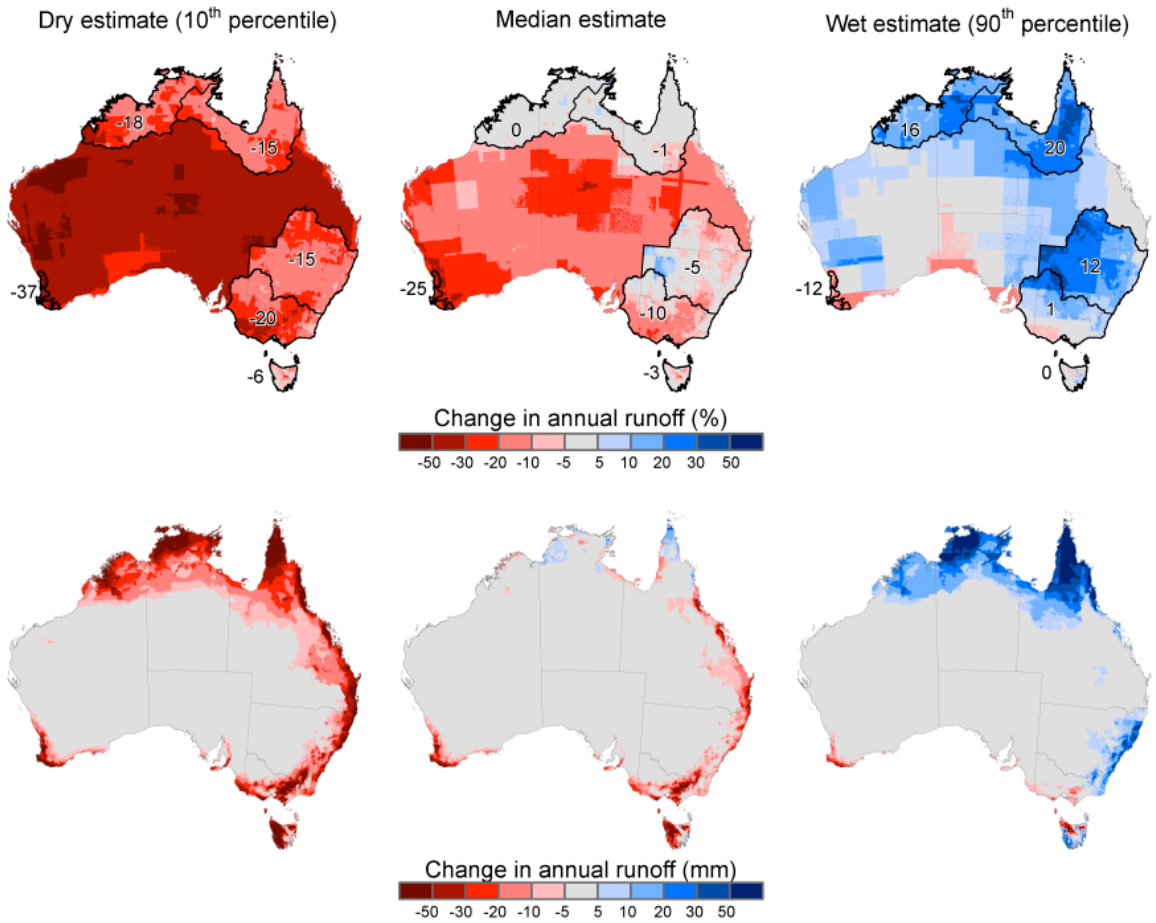


Figure 25-4: Projected changes in mean annual runoff for a 1°C global average warming. Figures show changes in annual run-off (percentage change; top row) and run-off depth (millimetres; bottom row), for median, dry and wet (10th and 90th percentile) range of estimates, based on hydrological modelling using catchment-scale climate data downscaled from AR4 GCMs (Chiew *et al.*, 2009; CSIRO, 2009b; Petheram *et al.*, 2012; Post *et al.*, 2012). Projections for a 2°C global average warming are about twice that shown in the plots (Post *et al.*, 2011). Figure adapted from (Chiew and Prosser, 2011; Teng *et al.*, 2012).

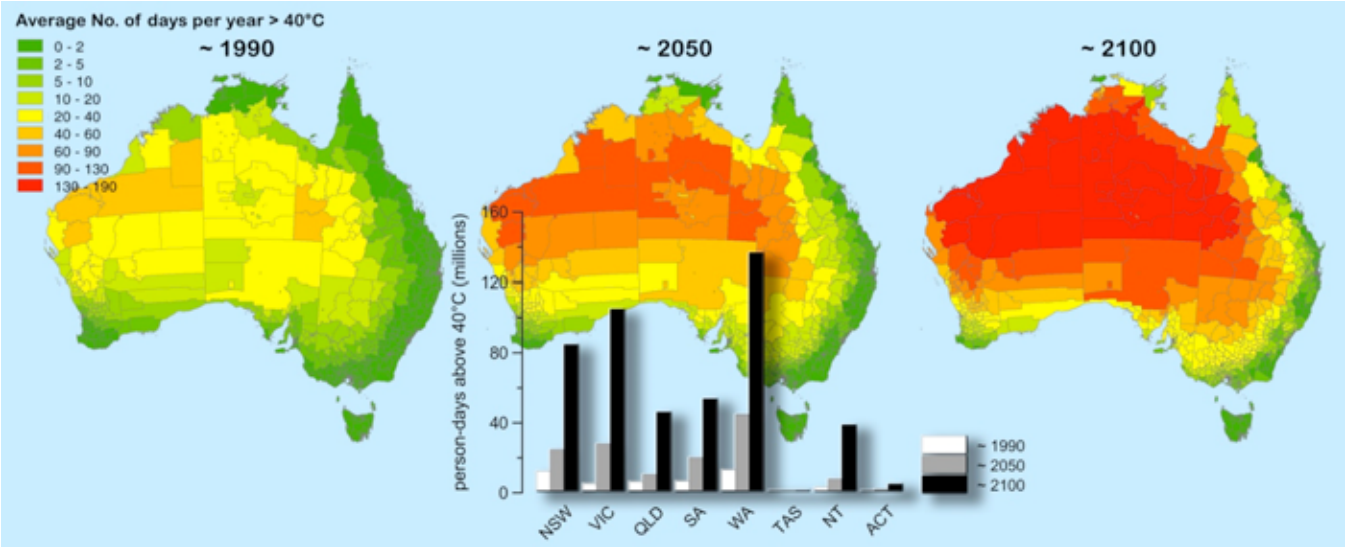


Figure 25-5: Projected changes in exposure to heat under a high emissions scenario (A1FI). Maps show the average number of days with peak temperatures >40°C for Australian statistical local areas, for ~1990 (based on available meteorological station data for the period 1975-2004), ~2050 and ~2100. Bar charts show the change in population heat exposure, expressed as person-days exposed to peak temperatures >40°C, aggregated by State/Territory and including projected population growth for a default scenario. Future temperatures are based on simulations by the GFDL-CM2 global climate model (Meehl *et al*., 2007), re-scaled to the A1FI scenario; simulations based on other climate models could give higher or lower results. Data from Baynes *et al*. (2012).

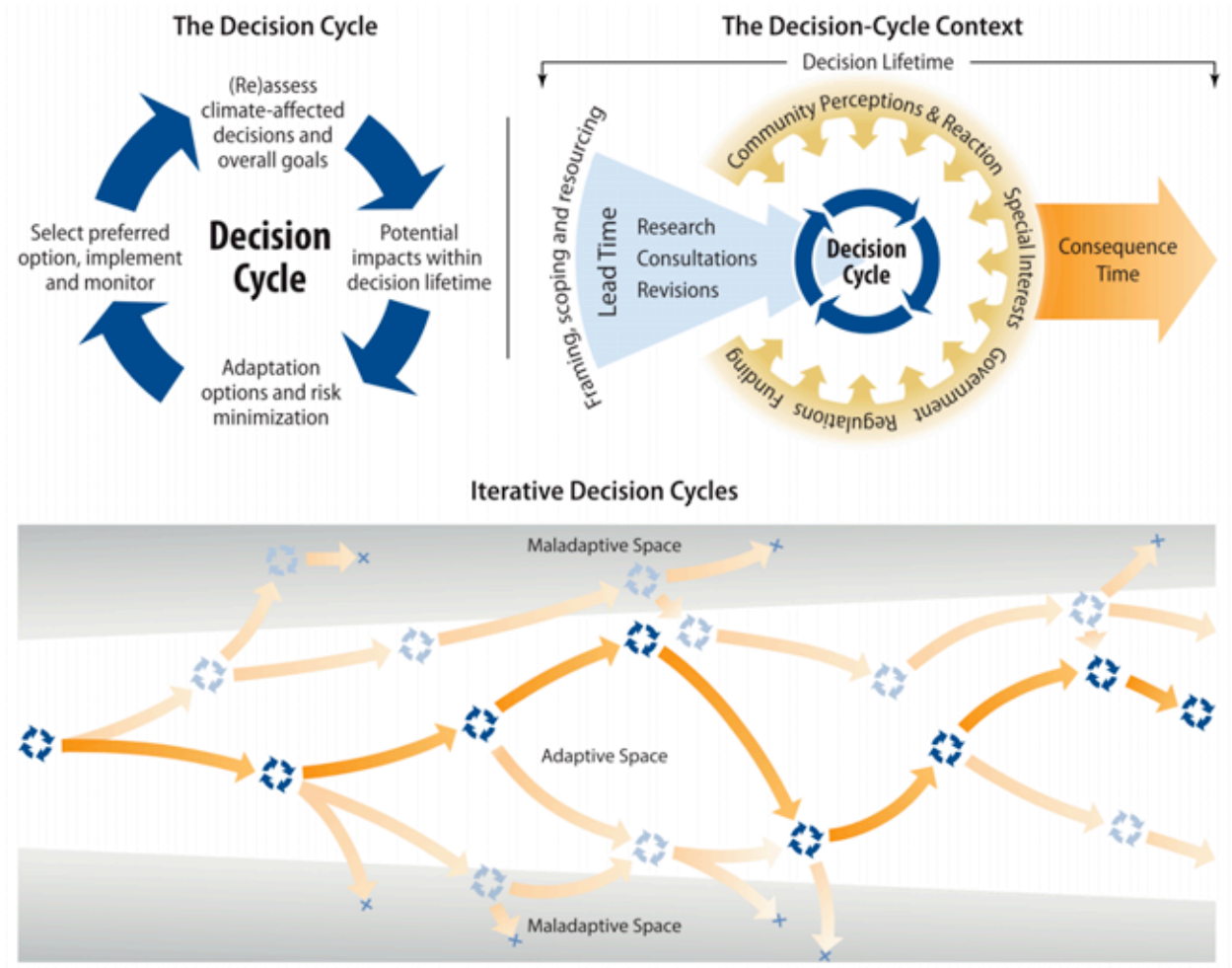


Figure 25-6: Schematic illustration of adaptation as an iterative risk management process. Each individual adaptation decision comprises well known aspects of risk assessment and management (top left panel). Each such decision occurs within and exerts its own sphere of influence, determined by the lead- and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single correct adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations and goals.

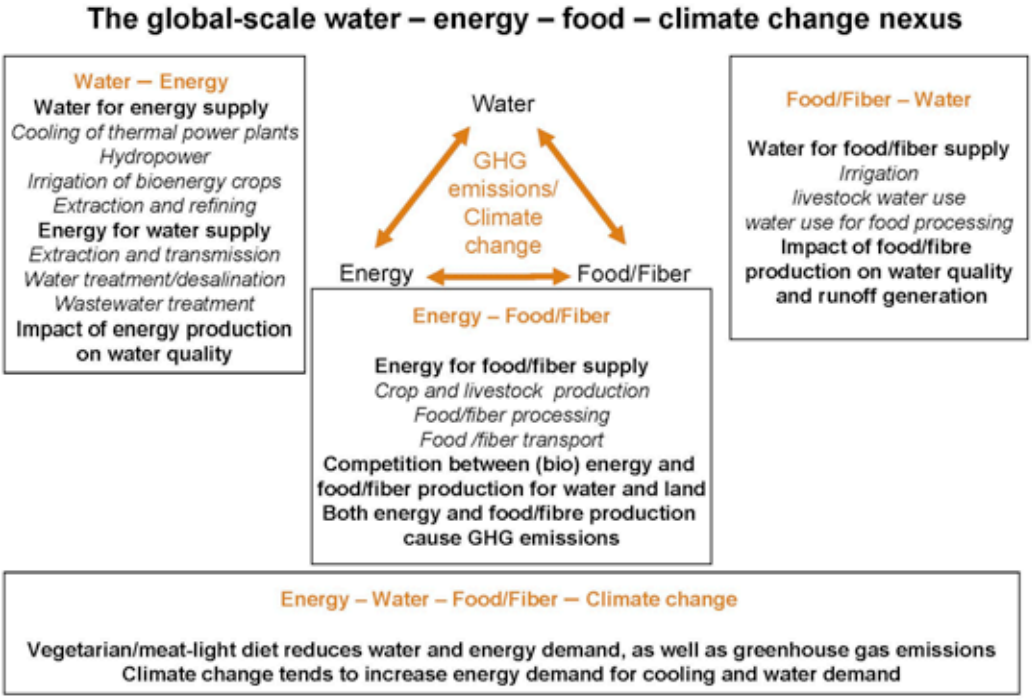


Figure WE-1: The water-energy-food nexus as related to climate change.

Chapter 26. North America

Coordinating Lead Authors
Patricia Romero-Lankao (Mexico), Joel B. Smith (USA)

Lead Authors
Debra Davidson (Canada), Noah Diffenbaugh (USA), Patrick Kinney (USA), Paul Kirshen (USA), Paul Kovacs (Canada), Lourdes Villers Ruiz (Mexico)

Contributing Authors
Hannah Brenkert-Smith (USA), Jessie Carr (USA), Anthony Cheng (USA), Thea Dickinson (Canada), Ellen Douglas (USA), Rob de Loë (Canada), Hallie Eakin (USA), Daniel M. Gnatz (USA), Mary Hayden (USA), Maria Eugenia Ibarraran Viniegra (Mexico), Elena Jiménez Cisneros (Mexico), Amrutasri Nori-Sarma (India), Landy Sánchez Peña (Mexico), Catherine Ngo (USA), Greg Oulahen (Canada), Diana Pape (USA), Ana Peña del Valle (Mexico), Roger Pulwarty (USA), Ashlinn Quinn (USA), Fabiola S. Sosa Rodrigquez (Mexico), Bradley H. Udall (USA), Jason Vogel (USA), Fiona Warren (Canada), Kate Weinberger (USA), Tom Wilbanks (USA), Olga Wilhelmi (USA)

Review Editors
Ana Rosa Moreno (Mexico), Linda Mortsch (Canada)

Volunteer Chapter Scientist
William Anderegg (USA)

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Frequently Asked Questions
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References

Executive Summary

Changes in climate trends in North America include **i**ncreased occurrence of severe hot weather events over much of the U.S., decreases in frost days, increases in heavy precipitation over much of North America, and reductions in spring snowpack along with an earlier peak runoff over many areas (*very high confidence*). **It is *highly likely* that global average increases in temperatures of at least 2°C (above the pre-industrial baseline) will lead North America to experience a frequent occurrence of**:

- **Extreme heat** during the summer in most areas
- **Low snow years and shifts towards earlier snowmelt runoff** in areas where seasonal snow cover is present in the current climate. [26.2]

It is *likely* that global warming of approximately 4°C will cause increases in annual precipitation in northern North America and decreases in annual precipitation in southern North America.

Attribution of observed changes in North America to anthropogenic climate change has been established for some physical systems (e.g., snowpack) and some ecosystems (e.g., forests dieback and pests distribution) (*very high confidence*). Evidence of anthropogenic climatic influence on agriculture, water, and human settlements is less clearly established.

Impacts of climate variability such as floods, decreased water availability, and increased salinity of coastal water supplies, which are exacerbated by other anthropogenic drivers, are observed in most areas of North America (*high confidence*). Water supply deficits are conducive to adaptive response, with many hard and soft approaches to adaptation currently available; adaptive responses to flooding and water quality concerns are more limited (*high confidence*). [26.3] **It is *very likely* that the 21st century will witness:**

- **Decreases in water quality, and increases in flooding and droughts, throughout most of North America** under climate change, and these impacts exacerbated by other anthropogenic drivers.
- **Decreases in water supplies for urban areas and irrigation in selected areas** of North America with confounding effects of development, except in general for *southern Mexico*; the northwest and northeast coastal USA; and west and east Canada. [26.3, 26.8]

Climate change is already affecting many ecosystems across North America. A global increase of 2°C would have widespread adverse impacts on those ecosystems (*high confidence*). Forests are being affected by fire, drought, pests, and other climate-related stresses. Coastal zones are being affected by multiple and often interacting climate stresses including higher temperatures, ocean acidification, coral reef bleaching, sea level rise, storm surges, and storms. Climate stresses will *likely* reduce biodiversity and ecosystem services. [26.4]

Without adaptation, projected changes in temperature, precipitation, and extreme events would result in notable productivity declines in major North American crops by the end of the 21st Century (*very high confidence*). Given that North America is a significant source of global food supplies, if projected productivity declines here are not addressed with substantial investments in adaptation, there will likely be a negative effect on global food security (*medium confidence*). Adaptation may ameliorate many climate impacts to North American agriculture, but the institutional support mechanisms currently in place are insufficient to ensure effective, equitable and sustainable adaptation strategies (*medium confidence*). [26.5]

Human *health impacts* from extreme events have been observed. Heat extremes currently result in increases in mortality and morbidity in North America, with impacts that vary by age and socioeconomic factors (*very high confidence*). Coastal storm events periodically cause excess mortality and morbidity via a range of direct and indirect pathways in North America, particularly along the east coast of the United States, and the gulf coast of both Mexico and the United States (*high confidence*). The effect of increasing heat extremes on human health will depend on the pace of adaptation, which is unknown. Given current levels of adaptation, there are *likely* to be increased health impacts from heat extremes among vulnerable communities, populations, and individuals. Conditional on an increase in storm severity under a changing climate, there are likely to be continued human health risks in the absence of specific adaptation planning. [26.6]

Several social and economic impacts observed in North American human settlements have been attributed, with different degrees of certainty, to climate-related processes (*high confidence*). These processes include but are not limited to sea level rise, changes in temperature and precipitation, and occurrences of such extreme events as droughts and storms. [26.8]

Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific social and environmental factors and processes (*high confidence*). Some of these processes (e.g., the legacy of previous and current stresses) are common to urban and rural settlements, while others are more pertinent to some types of settlements than others. For example, concentrations of populations, economic activities, cultural amenities, and built environments in highly exposed urban locations such as coastal and dry areas creates higher hazard risks in cities; whereas, for many small rural areas, geographic isolation and institutional deficits are key sources of vulnerability. **Among the most vulnerable are indigenous peoples** due to their unique history and relationship to the land, and Mexico City due to the high density of population combined with several socio-economic and environmental sources of vulnerability (*high confidence*). [26.8]

Many infrastructural elements across North America are currently vulnerable to extreme weather events and, unless investments are made to strengthen them, would be more vulnerable to climate change (*medium confidence*). Infrastructures, particularly in water resources and transportation, are in many cases deteriorating, thus more vulnerable to extremes than strengthened ones. Extreme events have caused significant damage to infrastructure in many parts of North America. Risks to infrastructure are particularly acute in Mexico. [26.7]

Most sectors of the North American economy have been affected by and responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). There are, however, few examples of proactive adaptation anticipating future climate impacts, and these are largely found in sectors with longer term decisionmaking, including energy and public infrastructure. Lessons learned are not well-documented in the literature. [26.7]

There is an emerging concern that dislocation in one sector of the economy may have an adverse impact on other sectors due to supply chain interdependency (*medium confidence*). [26.7]

Slow onset perils – like sea level rise, drought, and permafrost melt – are another emerging concern for some sectors, with large regional variation in awareness (*medium confidence*). There is little published literature about impacts and adaptation experience. [26.7]

Different economic and demographic sectors are responding to climate change (e.g., purchasing additional insurance, reinforcing homes to withstand extreme weather). **While different tiers of government are assessing their climate vulnerabilities and designing adaptation actions and programs**, **there has been more** l**eadership in adaptation planning at the local level.** Many governmental responses are in diagnosis and planning stage and have not yet moved into implementation (*high confidence*). [26.8, 26.9]

Important barriers exist to effective adaptation such as path dependency**,** lack of assets and options, lack of funding and staff, lack of horizontal and vertical coordination, asymmetries in access to information, lack of social capital, and top-down decisionmaking (*high confidence*). [26.8, 26.9]

Climate change impacts can hamper progress towards sustainability and have the potential to exacerbate existing challenges such as deficits in infrastructure or in institutional capacity to promote the health and well-being of human populations (*high confidence*). [26.7, 26.9]

Adaptation actions at the local level throughout North America have the potential to result in synergies, conflicts, or tradeoffs with mitigation and other development actions and goals (*high confidence*). For example, reductions in greenhouse pollutant emissions will in many cases bring proximal benefits for human health by reducing health-damaging air pollution concentrations. Conversely, sea walls can protect coastal properties, yet may negatively affect the structure and function of coastal ecosystems. [26.8]

26.1. Introduction

This chapter assesses literature on observed and projected impacts, vulnerabilities and risks as well as on adaptation practices and options in three North American countries: Canada, Mexico and USA. (The North American Arctic region is assessed in Chapter 28: Polar Regions). North America ranges from the tropics to frozen tundra, and contains a diversity of topography, ecosystems, economies, governance structures and cultures. As a result, risk and vulnerability to climate variability and change may differ considerably across the continent depending on geography, scale, hazard, social, socio-ecological or ecological systems, demographic sectors, cultural values and institutional settings (Table 26-1). This chapter seeks to take account of this diversity and complexity as it affects and is predicted to affect vulnerability and risk across North America.

No single chapter would be adequate to cover the range and scope of the literature about climate change impacts, vulnerabilities and adaptations in our three focus countries. (Interested readers are encouraged to review the following reports: Canadian Climate Report; (SEMARNAT-INECC, 2012; NCADAC, 2013). We, therefore, attempt to take a more integrative and innovative approach. In addition to describing current and future climatic and socioeconomic trends of relevance to understanding risk and vulnerability in North America (section 26.2), we contrast climate impacts, vulnerabilities and adaptations across and within the three countries in the following key sectors: water resources and management (section 26.3); ecosystems and biodiversity (section 26.4); agriculture and food security (section 26.5); human health (section 26.6); and infrastructures and other economic sectors (section 26.7). We use a comparative approach to explore the factors and processes associated with differences and commonalities in vulnerability, risk and adaptation between urban and rural settlements (section 26.8); and to illustrate and contrast the nuanced challenges and opportunities adaption entails at the city, the state and the national level (sections 26.8.4 and 26.9; Box 26-3). We highlight two case studies that cut across sectors, systems or national boundaries. The first, on wildfires (Box 26-2), explores some of the connections between climatic and physical process (e.g., decadal climatic oscillation, droughts, wildfires and pests) and across systems and sectors (e.g., fires direct and indirect impacts on local economies, livelihoods, built environments and human health). The second takes a look at the world's longest border between a high-income (US) and middle income country (Mexico) and briefly reflects on the challenges and opportunities of responding to climate change in a transboundary context (Box 26-1).

We close with a section (26.10) summarizing key multi-sectoral risks and uncertainties at the regional level and discussing some of the knowledge gaps that will need to be filled by future research.

Findings from the Fourth Assessment Report

This section summarizes key findings on North America, as identified in chapters 13 and 14 of the Fourth IPCC assessment focused on Mexico (Magrin *et al*., 2007) *and Canada and the USA respectively* (Field *et al*., 2007). Over the past decades, economic damage, from severe weather has increased dramatically, due largely to the high value of infrastructures at risk in Canada and the US (14.2) (*very high confidence*). Increases in the frequency of very heavy rains were identified in central Mexico [13.2.4.1] (*high confidence*).

Although Canada and the US have considerable adaptive capacity, their vulnerability depends on the effectiveness and timing of adaptation and the distribution of capacity, which vary spatially and among sectors [14.2.6, 14.4] (*very high confidence*). Mexico has early warning systems and risk analysis in such areas as agriculture, human health and water resources, yet it faces planning and management barriers (*high confidence*). In Canada and the US, based upon long standing traditions and institutions, a decentralized response framework has resulted in adaptation that tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems [14.5] (*very high confidence*).

Coastal communities and habitats in the three countries will be stressed by sea level rise, storm-surge flooding and other climate change impacts interacting with developmental and environmental stresses, such as salt intrusion, pollution, population growth and the rising value of infrastructure in coastal areas (Mexico: [13.4.4]) (*high confidence*); (US and Canada: [14.2.3; 14.4.3) (*very high confidence*).

Land use changes in Mexico have intensified land degradation, and increased the vulnerability of coastal mangroves and estuaries [13.2.3] (*high confidence*). Significant species extinctions in many tropical areas of Mexico are projected [13.4.1] (*high confidence*). While increases in grain yields in U.S. and Canada are likely [14.4.4], in Mexico the picture is mixed for wheat and maize, whose behavior is more erratic depending on the scenario that plays out [13.4.2] (*medium confidence*).

Millions in Mexico are projected to be at risk from the lack of adequate water supplies [13.4.3] (*medium confidence*), while in the US and Canada rising temperatures will diminish snowpack and increase evaporation, thus affecting seasonal availability of water [14.2.1] (*very high confidence*). Together with higher demand from economic development, agriculture and population growth will impose further constrains to over-allocated water resources, increasing competition among agricultural, municipal, industrial and ecological uses [14.4.1; 14.4.6] (*very high confidence*).

Changes in geographical distribution and transmission of diseases have been projected for the three countries. Mexico will likely face changes in the geographical distribution of dengue [13.4.5], while the US and Canada are likely to see an increase in risk and geographic distribution of vector-borne infectious diseases, including Lyme disease and West Nile virus. Warming and climate extremes are also likely to increase respiratory illness, including exposure to pollen and ozone [14.4]. Hot temperatures and extreme weather in Canada and the US are likely to increase adverse health impacts from heat-related mortality. Climate change impacts on infrastructure and human health and safety in urban centers of Canada and the US will be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth and an aging population [14.4; 14.5] (*very high confidence*).

A warmer future with drier soils and longer growing seasons will also likely increase and intensify wildfire and insect outbreaks in Canada and the US. Pressure for species to shift north and to higher elevations will fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function and services [14.2; 14.4] (*very high confidence*).

Without increased investments in such countermeasures as early warning and surveillance systems, air conditioning, access to health care, pollution, storm-related fatalities and injuries, and infectious diseases, hot temperatures and extreme weather in Canada and the US are likely increase adverse health impacts from heat-related mortality. Furthermore, climate change impacts on infrastructure and human health and safety in urban centers of Canada and the US will be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth and an aging population [14.4; 14.5] (*very high confidence*).

How vulnerable North America is depends upon the effectiveness of adaptation and the distribution of capacity. Both of these are unevenly distributed [14.5]. While both chapters see 'mainstreaming' climate issues into decision making as key to successful adaptation [14.5; 13.5], chapter 13 suggests mainstreaming adaptation strategies with national / regional sustainable development plans [13.5] as a key step towards meeting adaptation needs.

26.2. Key Trends

26.2.1. Demographic and Socioeconomic Trends

26.2.1.1. Current Trends

Canada, Mexico and USA share commonalities but also differ in key dimensions shaping vulnerability and adaptation such as population dynamics, economic development, and institutional capacity. Population growth has been slower in Canada and USA than in Mexico (United Nations, 2011). Yet population growth in Mexico also decreased from 3.4 percent during 1970-1980 to 1.5 percent during the last decade due to lower birth rates, which were offset by gains in life expectancy. All three countries have aging populations. In 2010, 20% of the population in Canada was 60 years and older, compared to 18% in the USA, and 9% in Mexico (United Nations, 2011). Urban populations have grown faster than rural populations resulting in a North America that is highly urbanized (Canada 84.8%, Mexico 82.8% and USA 85.8%). These urban populations are also expanding into peri-urban spaces, producing rapid changes in *population patterns* and land use that can exacerbate climate risks (Eakin *et al*., 2010; Romero-Lankao *et al*., 2012).

Similarly, while concentrations of growing populations, infrastructures and sectors in urban areas can be a source of risk, geographic isolation of rural populations can be a source of sensitivity that is aggravated by high dispersion levels (Figure 26-1; section 26.8). Rural populations might experience an increased sensitivity to climate events, as they face smaller labor markets, lower income levels and reduced access to public services. Rural poverty could also be aggravated by agricultural changes, particularly in Mexico where 65% of the rural population is poor, agricultural production is seasonal and most households lack insurance (Scott, 2007). Food price increases, which may also result from climate events, would contribute to poverty levels in urban and rural areas (Lobell *et al*., 2011; World Bank, 2011).

[INSERT FIGURE 26-1 HERE
Figure 26-1: Current and future populations in North America. While concentrations of growing populations, infrastructures, and sectors in urban areas can be a source of risk, geographic isolation of rural populations can be a source of sensitivity that is aggravated by high dispersion levels. Source: Lutz, 2007.]

The three countries have become more economically integrated following the 1994 North American Free Trade Agreement. For instance, prior to a 2007-2008 reduction in trade, the US-Mexico border was a region of dynamic growth in industry, employment and global trade of agricultural and manufactured goods (Robertson *et al*., 2009). However, differences in such determinants of adaptive capacity as levels of human development within and across countries, institutional asymmetry and fragmentation can be a source of risks and opportunities in managing trans-border environmental resources and vulnerability issues (Scott and Banister, 2008; Wilder *et al*., 2010) (Box 26-1).

_____ START BOX 26-1 HERE _____

Box 26-1. Adapting in a Transboundary Context: the Mexico-US Border Region

Extending over 3169 km (1969 miles), the border between the United States and Mexico is one of the longest between a high-income and middle income country, and offers both challenges and opportunities to respond to climate change in a transboundary context. Sharing common climate regimes, natural resources, regional economies and urban areas (Wilder *et al*., 2013), in recent years the region has been subject to severe droughts, and floods, and these events are likely to become more frequent and intense as climate change progresses (Wilder *et al*., 2013). Additionally, there is a prevalence of incipient or actual conflict, given by currently or historically contested land boundaries or natural resources (Udall and Varady, 1993) and management of shared resources by distinct entities (Megdal and Scott, 2011).Climate change, therefore, as it interplays with socio-economic changes in the area, will most likely bring significant consequences for water resources, ecosystems, human health, and rural and urban settlements.

Changing Socio-Economic and Physical Conditions

The population of the Mexico-US Border Region is rapidly growing and urbanizing, with population increasing from just under 7 million in 1983 to over 15 million in 2012. Since 1994, rapid growth in the area has been fueled by a fast-paced economic change resulting from the passage of the North American Free Trade Agreement (NAFTA) (U.S. EPA and Secretaría de Medio Ambiente y Recursos Naturales, 2011; U.S. EPA, 2012). Between 1990 and 2001 the number of maquiladoras in Mexico had more than doubled, from 1700 to nearly 3,800, *with* 2,700 in the border area. By 2004, it was estimated that more than one million Mexicans were employed in the more than 3,000 *maquiladoras* located along the border.

Notwithstanding this explosive growth in economic activity and population in the region, challenges to adaptive capacity include high rates of poverty in a landscape of uneven economic development (Wilder *et al*., 2013). Large sections of the urban population live in informal housing lacking the health and safety standards needed to respond to hazards, and with no insurance (Collins *et al*., 2011). Any effort to increase regional adaptive capacity needs to take existing gaps into account.

Climate change is projected to put additional stresses to the region (Wilder *et al*., 2013), currently characterized by high temperatures and aridity, with about half of its precipitation coming in the summer monsoon and that has experienced particularly dry conditions in recent years. For example, the current drought, affecting large areas on both sides of the border is the most extreme in over a century of recorded precipitation patterns for the area (Cayan *et al*., 2010; Seager and Vecchi, 2010b; Nielsen-Gammon, 2011). Streamflow in already oversubscribed rivers such as the Colorado and Rio Grande has also decreased, threatening water resources. Climatological conditions for the area have been particularly unprecedented, with sustained high temperatures that may exceed any experienced for 1,200 years. While these changes cannot conclusively be attributed to anthropogenic climate change, they are consistent with climate change projections (Woodhouse *et al*., 2010).

Ecosystems

Population growth, economic development and urbanization are already fragmenting and degrading the region's highly diverse habitats, species and ecosystems, such as the California saga and chaparral, the Sonoran and Chihuahuan deserts, sensitive wetlands and the Tamaulipan mezquital (Wilder *et al*., 2013). Of the region's over 6,500 animal and plant species, 235 on the Mexican side are classified in a risk category and 85 are considered endangered under Mexico's law. While on the U.S. side, 148 species are listed as endangered under the U.S. Endangered Species Act. (U.S. EPA and Secretaría de Medio Ambiente y Recursos Naturales, 2011).

Human Health

In the absence of adequate policies and governance structures, upward trends in population growth and economic activity have brought with them more pollution sources, including motor vehicles, industries and power plants (Varady *et al*., 2002; Sarnat *et al*., 2012). Heavy diesel trucking is also concentrated along several highways and border crossings, creating local hotspots for fine particle pollution (Svendsen *et al*., 2012). Border monitoring stations show that there were some days with violations of ozone or PM10 air quality standards in the past five years, but with variations from year to year (World Health Organization, 2007).

As climate change enters the equation, it may impact human health in the region in diverse ways: For instance, long-term draught in the region increases respiratory impacts from wind-blown dust. Rising temperatures increase ozone levels (U.S. EPA and Secretaría de Medio Ambiente y Recursos Naturales, 2011). As climate change interacts with socio-economic factors in the region, the human health stressors may be compounded.

Adaptation Challenges

In the fragile ecosystems of this region, opportunities and challenges, resources and environmental and health impacts are shared across international borders, creating the need for cooperation among local, national and international actors. Although there are examples of efforts to manage trans-border environmental problems (Wilder *et al*., 2010; Megdal and Scott, 2011), barriers to effective cooperation and collaboration exist such as different governance structures —centralized (Mexico) versus decentralized (United States); institutional fragmentation; asymmetries in the use and dissemination of information, and language (Wilder *et al*., 2013).

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26.2.1.2. Future Trends

Population in North America is projected to keep growing over the next decades and reach between 531.8 and 660.1 million by 2050 based on respective B2 and A2 scenarios (Lutz *et al*., 2007). The aging of population is also projected to progress, particularly in Mexico, so that by 2050, between 26.9% and 23.4% of the population in Canada, 18.4 % and 12.4% Mexico and 20.9% and 17.3% in the USA is projected to be elderly under respective B2 and A2 scenarios (Lutz *et al*., 2007). The elderly are more sensitive to extreme weather events (heat waves in particular, Figure 26-2) and the risks are still greater for those living alone (Martiello and Giacchi, 2010; Diffenbaugh and Scherer, 2011; Romero-Lankao, 2012; White-Newsome *et al*., 2012). Increases in the numbers of single-person households and female-headed households may also exacerbate the vulnerability of populations. Institutional capacity may also be limited by challenges posed by aging populations and a resulting stress on health and economic performance.

[INSERT FIGURE 26-2 HERE
Figure 26-2: Projected changes in the intensity of the worst heat events, as simulated by CLMU for urban grid cells: a) near term (2020-2039) relative to present-day climate (1980-1999); b) end of the 21st century (2080-2099) relative to present-day climate (1980-1999). Source Wilhelmi et al. (forthcoming).]

While many demographic factors have bearing on impacts and adaptation, three other shifts are projected to influence impacts, vulnerabilities and adaptation to climate change in North America: urbanization, migration, and economic disparity. With small differences between countries, both the concentration of growing populations in some urban areas and the dispersion of rural populations in many smaller settlements are projected to continue to define North America by 2050 (Figure 26-1b). For instance, according to projections, giving no consideration to global warming, between 2005 and 2030 the population of Mexico-City-Metro-Area will increase by 17.5%, while between 2007 and 2030 available water will diminish by 11.2% (Romero-Lankao, 2010). Conversely, education, a key determinant of adaptive capacity, is expected to expand to low-income households, minorities, and women, which could increase the capcity of households to cope with environmental risks and have a positive impact on economic growth (Goujon and Lutz, 2004). However, a continued growth in economic disparity and poverty could hinder such improvements. Inequality in Mexico is larger, having a Gini index (a measure of economic disparity) of 0.56, in contrast to 0.317 for Canada and 0.389 for USA (OECD, 2010b). Limited economic growth expected in the short run for the region would not help to reduce the income gap across and within countries (OECD, 2010a). Mexico, which already has a markedly higher poverty rate than Canada or the U.S., is one of five developing countries in the world that is projected to experience the highest increases in poverty due to climate-induced extreme events (52% increase in rural households; 95.4% in urban wage-labor households) (CMIP3, A2) (Ahmed *et al*., 2009).

Migration can be influenced by multiple factors, and isolating climate change as a cause is difficult. However, changes in climate can influence decisions to migrate, and migration flows themselves have implications for climate

change impacts and vulnerability. This because the arrival migrants can increase pressure on climate sensitive urban regions (Hugo, 2011). In North America, one of the most significant migration flows that was influenced, in part, by climate change was the outmigration of many in the Mexican agrarian sector (Saldaña-Zorrilla and Sandberg, 2009). Lack of capital has been the key inducement for migration in response to historic Mexican droughts (Fraser, 2007; Gilbert and McLeman, 2010). However, current outmigration from regions in Mexico experiencing recurrent disasters outpaces migration from regions with lower socio-economic status (Saldaña-Zorrilla, 2006) pointing to concerns for health and safety as another driver of migration resulting from changes in climate.

26.2.2. Physical Climate Trends

Some processes important for climate change in North America are assessed in other Chapters of AR5, including WGI Chapter 2 (*Observations: Atmosphere and Surface*), WGI Chapter 14 (*Climate Phenomena and their Relevance for Future Regional Climate Change*), WGI Annex I (*Atlas of Global and Regional Climate Projections*), and WGII Chapter 21 (*Regional Context*). In addition, comparisons of emissions, concentrations, and radiative forcing in the RCPs and SRES scenarios can be found in WGI Annex II (*Climate System Scenario Tables*).

26.2.2.1. Current Trends

Chapter 2 of WGI assesses observations of the climate system. Observations show increases in the occurrence of severe hot events over the U.S. over the late 20th century (Kunkel *et al.*, 2008, WGI 2.6.1), a result in agreement with observed late-20th-century increases in extremely hot seasons over a region encompassing northern Mexico, the U.S. and parts of eastern Canada (Diffenbaugh and Scherer, 2011). These increases in hot extremes have been accompanied by observed decreases in frost days over much of North America (Alexander et al., 2006; Brown *et al.*, 2010b, WGI 2.6.12), decreases in cold spells over the U.S. (Kunkel *et al.*, 2008, WGI 2.6.1), and increasing ratio of record high to low daily temperatures over the U.S. (Meehl *et al.*, 2009). However, relative cooling has occurred over central North America and the eastern USA (e.g., Alexander et al., 2006; Peterson *et al.*, 2008, WGI 2.6.1), with more pronounced contrast seen in trends over the past century than in trends over the last three decades (WGI Figure 2.22, Figure 26-3). It is possible that this "warming hole" has been influenced by changes in the hydrologic cycle (e.g., Pan *et al.*, 2004; Portmann *et al.*, 2009), as well as by decadal-scale variability in the ocean (e.g., Kumar *et al.*, 2012; Meehl *et al.*, 2012).

[INSERT FIGURE 26-3 HERE
Figure 26-3: Changes in annual temperature and precipitation. White indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.]

WGI notes that observations show increases in heavy precipitation over Mexico, the U.S. and Canada between the mid-20th century and the early 21st century (WGI 2.6.2, DeGaetano, 2009; Peterson and Baringer, 2009; Pryor *et al.*, 2009). Observational analyses of changes in drought are more equivocal over North America, with mixed sign of trend in dryness over Mexico, the U.S. and Canada (WGI 2.6.2 and Figure 2.42, Dai, 2011; Sheffield *et al.*, 2012). WGI notes evidence for earlier occurrence of peak flow in snow-dominated rivers globally (Rosenzweig, 2007, WGI 2.6.2). Observed snowpack and snow-dominated runoff have been extensively studied in the western U.S. and western Canada, with observations showing primarily decreasing trends in the amount of water stored in spring snowpack from 1960-2002 (with the most prominent exception being the central and southern Sierra Nevada)

(Mote, 2006) and primarily earlier trends in the timing of peak runoff over the 1948-2000 period (Stewart *et al.*, 2006). WGI also assess observed changes in extreme storms in North America, noting that observational limitations prohibit conclusions about trends in severe thunderstorms (WGI 2.6.2) and tropical cyclones (WGI 2.6.3). The most robust trends in extratropical cyclones over North America are determined to be towards more frequent and intense storms over the northern Canadian Arctic and towards less frequent and weaker storms over the southeastern and southwestern coasts of Canada over the 1953-2002 period(WGI 2.7.4, Wang *et al.*, 2006).

WGI concludes that it is "*virtually certain* that globally mean sea level (GMSL) has risen at a mean rate between 1.4 to 2.0 mm yr^{-1} over the 20th Century and between 2.7 and 3.7 mm yr^{-1} since 1993." (WGI 3 Executive Summary). In addition, WGI concludes that observed changes in extreme sea level have been caused primarily by increases in mean sea level (WGI 3.7.5). WGI also concludes that regional variations in the observed rate of sea level rise can result from processes related to atmosphere and ocean variability (such as lower rates along the west coast of the U.S.) or vertical land motion (such as high rates along the U.S. Gulf Coast), but that the persistence of the observed regional patterns is unknown (WGI 3.7.3).

26.2.2.2. Climate Change Projections

Chapter 14 of the WGI contribution to the AR5 assesses processes important for regional climate change, with section 14.7.3 focused on North America. Many of the WGI conclusions are drawn from Annex I of the WGI contribution to the AR5.

The CMIP5 ensemble projects very likely annual warming over North America, with very likely increases in temperature over all land areas in the mid- and late-21st-century periods of RCP4.5 and RCP8.5 (Figure 26-4). Mean warming across climate models exceeds 2°C over most land areas of all three countries in the mid-21st-century period of RCP8.5 and the late-21st century period of RCP4.5, and exceeds 4°C over most land areas of all three countries in the late-21st-century period of RCP8.5. The largest mean warming occurs over the high latitudes of the United States and Canada, as well as much of eastern Canada, including greater than 6°C of annual warming in the late-21st-century period of RCP8.5. The smallest mean warming occurs over areas of southern Mexico, the Pacific Coast of the United States, and the southeastern United States.

[INSERT FIGURE 26-4 HERE
Figure 26-4: Observed and simulated variations in past and projected future annual average precipitation and temperature over land areas of Canada, the contiguous United States, and Mexico. Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

Most land areas north of 45°N exhibit likely increases in annual precipitation in the late-21st-century period of RCP8.5, including very likely increases over the high latitude areas of North America (Figure 26-3). In contrast, much of Mexico and the southcentral and southwestern United States exhibit likely decreases in annual precipitation in the late-21st-century period of RCP8.5. Likely changes in annual precipitation are much less common at lower levels of forcing, with few areas of Mexico exhibiting changes that exceed the baseline variability in the mid- or late-21st-century periods of RCP4.5 or the mid-21st-century period of RCP8.5. Likewise, likely changes in annual precipitation in the United States are primarily confined to increases over the northern latitudes during the mid- and late-21st-century periods of RCP4.5, and the mid-21st-century period of RCP8.5. Very likely changes in annual precipitation are confined primarily to increases over the high latitude areas of North America throughout the illustrative RCP periods, with very likely increases occurring in the mid-21st-century period of RCP4.5 and becoming generally more wide-spread at higher levels of forcing.

The CMIP5 ensemble projects warming in all seasons over North America beginning as early as the 2016-2035 period of RCP2.6, with the greatest warming occurring in winter over the high latitudes (WGI Annex I and Figure

26-4; Diffenbaugh and Giorgi, 2012). An important measure of the robustness of climate change is the magnitude of the change ("signal") relative to the background climate variability ("noise"). From the perspective of impacts, adaptation and vulnerability, the "signal-to-noise ratio" helps to quantify the magnitude of climate changes relative to the background variability to which natural and human systems are accustomed in the recent climate. The CMIP5 and CMIP3 ensembles suggests that the response of warm-season temperatures to elevated radiative forcing exhibits higher signal-to-noise ratio than the response of cold-season temperatures (Diffenbaugh and Scherer, 2011; Kumar *et al.*, 2012), and the CMIP3 ensemble suggests that the response of temperature in low-latitude areas of North America exhibits higher signal-to-noise ratio than the response of temperature in high-latitude areas (Diffenbaugh and Scherer, 2011). In addition, CMIP3 and a high-resolution climate model ensemble suggest that the signal-to-noise ratio of 21st century warming is far greater over the western U.S., northern Mexico and the northeastern U.S. than over the central U.S. (Diffenbaugh *et al.*, 2011).

CMIP5 projects increases in winter precipitation over Canada and Alaska, consistent with projections of poleward shift in the dominant cold-season stormtracks (WGI 14.7.3, Yin, 2005), extratropical cyclones (Trapp *et al.*, 2009) and areas of moisture convergence (WG1 14.7.3), as well as with projections of shift towards positive North Atlantic Oscillation (NAO) trends (WGI 14.7.3, Hori *et al.*, 2007). CMIP5 also projects decreases in winter precipitation over the southwestern U.S. and much of Mexico associated with the poleward shift in the dominant stormtracks and the expansion of subtropical arid regions (WGI14.7.3, Seager and Vecchi, 2010b). However, there are uncertainties in hydroclimatic change in western North America associated with the response of the tropical Pacific sea surface temperatures (SSTs) to elevated radiative forcing (particularly given the influence of tropical SSTs on the Pacific North American pattern (PNA) and north Pacific storm tracks) (WGI 14.7.3, Cayan *et al.*, 1999; Findell and Delworth, 2010; Seager and Vecchi, 2010a), and not all CMIP5 models simulate the observed recent hydrologic trends in the region (Kumar *et al.*, 2012)

Mexico and the western U.S. emerge as prominent areas of aggregate climate change in both RCP4.5 and RCP8.5, primarily as result of extreme heat in all seasons and extreme dry conditions in winter and spring (Diffenbaugh and Giorgi, 2012). CMIP5 projects substantial increases in the occurrence of extremely hot seasons over North America in early, middle and late 21st century periods of RCP8.5, including greater than 80% of summers exceeding the late 20th century maximum during the 2070-2099 period (Diffenbaugh and Giorgi, 2012). The CMIP5 ensemble also projects substantial decreases in snow accumulation over the U.S. and Canada, including greater than 80% of years with March snow amount below the late 20th century median – and greater than 30% of years below the late 20th century minimum – over much of the western U.S. and western Canada beginning the middle 21st century period of RCP8.5 (Diffenbaugh *et al.*, 2012). These decreases in spring snow amount are associated with substantial changes in the timing of total surface runoff, including greater than 30% of years above (below) the baseline winter (spring) runoff over the high elevation areas of the western U.S. and western Canada during the 2070-2099 period, greater than 50% of years below the summer maximum runoff over the high elevations of northwestern Canada, and greater than 30% of years above the baseline winter maximum runoff over most of central Canada during the 2070-2099 period (Diffenbaugh *et al.*, submitted) .

26.3. Water Resources and Management

26.3.1. Observed Impacts on Water Resources

Drought: Although no evidence has yet been found indicating trends of increased drought occurrence at the North American continental scale (section 26.2.2.1.1., USCCSP, 2008), local trends over the past approximately 40 years have been observed in east and southwest USA, north and northwest Mexico, and the Canadian Prairies (Barnett *et al.*, 2008; Groisman and Knight, 2008; Ellis *et al.*, 2010; SEMARNAT-INECC, 2012, section 26).

Floods: Changes in the magnitude or frequency of flood events are difficult to attribute to climate change. Floods are generated by multiple mechanisms affected by numerous influences such as land use change, urbanization and flow regulation (section 26.2.2.1, Villarini *et al.*, 2011; SEMARNAT-INECC, 2012). For instance, in the eastern USA, the relationship between heavy rainfall and flooding shows a large annual variability that is not easily associated with changing climate (Smith *et al.*, 2011).

Mean Annual Streamflow: While annual precipitation and runoff increases have been found in the Midwestern and Northwestern United States, decreases have been observed in southern states (Georgakakos *et al*., 2013).

26.3.2. Water Use

Water withdrawals are already exceeding stressful levels (exceeding 40 percent of supply) in many regions of North America such as the southwest US, northern and central Mexico (particularly Mexico City), southern Ontario and the southern Canadian Prairies (National Water Commission of Mexico, 2010; Romero-Lankao, 2010; Sosa-Rodriguez, 2010; Averyt *et al*., 2011; Environment Canada, 2013a).

10 % to 30 % of the water quality monitoring sites in Mexico have polluted or heavily polluted water, depending upon the parameter monitored (National Water Commission of Mexico, 2010), and about 44% of assessed stream miles, and 64% of assessed lake areas in the US were not clean enough to support uses such as fishing and swimming (U.S. EPA, 2004). Conversely the stations in Canada's 16 most populated drainage basins reported at least fair quality, with many basins reporting good or excellent quality (Environment Canada, 2013b).

As noted in Section 26.7, the water resources management infrastructure in most areas of North America is in need of repair, replacement or expansion.

26.3.3. Projected Impacts and Risks

26.3.3.1. Water Supply

Most of the discussion focuses on surface water as there are few groundwater studies (Tremblay *et al*., 2011; Georgakakos *et al*., 2013).

In arid and semi-arid western USA and Canada and in most of Mexico, except the southern tropical area, water supplies are predicted to be further stressed by climate change (IMTA, 2010; MacDonald, 2010b; Montero Martinez *et al*., 2010), with expected changes varying based upon climate models, time frames and regions studied. For instance, along the United States-Mexico border under A2, A1B, and B1 scenarios for 2050 and 2080s, reduced water availability is anticipated to result from increasing temperatures and high degree of annual precipitation variability (Cayan *et al*., 2010; IMTA, 2010), resulting in possible surface and groundwater overexploitation (CONAGUA, 2011). Similarly, with scenarios A2 and A1B in 2039, the northeastern coast of Mexico will probably face high water stress due to the decreased availability and increased demand for water leading to overexploitation of groundwater even though the region already has many reservoirs (CONAGUA, 2011). Compounding factors will include salt water intrusion, and increased groundwater and surface water pollution (Leal *et al*., 2008).

In the US southwest and southeast, ecosystems and irrigation are projected to be particularly stressed by decreases in water availability and growing water demand, or by water transfers to urban and industrial users with greater economic productivity (Seager *et al*., 2009; Georgakakos *et al*., 2013) . In the Colorado River Basin crop irrigation requirements for pasture grass are projected to increase by 20% by 2040 and by 31 % by 2070 (AECOM, 2010). In the Rio Grande basin, New Mexico, runoff is projected to be reduced by nearly 30% by 2080. Water transfers entail significant transaction costs associated with adjudication and potential litigation. In addition, transferring water reduces ecological, environmental, social, and cultural attributes (Hurd and Coonrod, 2012).

Other parts of North America are projected to have different climate risks. For instance, while no vulnerability of water resources is projected for 2050 over the tropical southern region of Mexico, greater precipitation is projected after 2050, increasing the possibility of destroying hydropower and water storage dams by floods (IMTA, 2010). Throughout the 21st century, the cities of Seattle, Everett, and Tacoma, Washington, are projected to have drawdown of average seasonal reservoir storage in the absence of demand reduction because of less snowpack even though annual streamflows increase. Without accounting for demand increases, reliability of all systems can remain

above 98% for Seattle, Everett and Tacoma through mid and late century (Vano *et al.*, 2010a). Throughout eastern USA, water supply systems will be negatively impacted if groundwater recharge lessens and snowpack storage is lost as well as by rising sea levels, increased storm intensities, salt water intrusion, lower flows, land use, population changes, and other stresses (Sun *et al.*, 2008; Obeysekera *et al.*, 2011). Southern Alberta, where approximately two-thirds of Canadian irrigated land is found (Poirier and de Loë, 2012) is projected to experience declines in mean annual streamflow, especially during the summer (Shepherd *et al.*, 2010.). Decreases of 5% annual average runoff of the Chaudière River watershed, in Québec, Canada, were simulated for 2010-2039 relative to the reference period 1970-1999 using a variety of downscaling methods (Quilbe *et al.*, 2008; Chen *et al.*, 2011).

26.3.3.2. Water Quality

Reduced flow conditions can result in quality impacts due to increased temperature, increased concentrations of dissolved substances, and dissolved oxygen level changes (Novotny and Stefan, 2007; Delpla *et al.*, 2009.; Daley *et al.*, 2009; Benotti *et al.*, 2010). Increased wildfires linked to a warming climate are expected to affect water quality downstream of forested headwater regions (Emelko *et al.*, 2011). Model simulation of lakes under a range of plausible higher air temperatures (Tahoe, Great Lakes, Lake Onondaga and shallow polymictic lakes), depending on the system, predict a range of impacts such as increased phytoplankton, fish and cyanobacteria biomass, lengthened stratification periods with risks of significant hypolimnetic oxygen deficits in late summer with solubilization of accumulated phosphorous and heavy metals with accelerated reaction rates, and decreased lake clarity (Dupuis and Hann, 2009.; Trumpickas *et al.*, 2009; Sahoo *et al.*, 2010; Taner *et al.*, 2011). Model simulations have found seasonal climate change impacts on nonpoint source pollution loads, while others have found no impact (Marshall and Randhir, 2008; Tu, 2009; Praskievicz and Chang, 2011; Taner *et al.*, 2011). Tu (2009), Praskievicz and Chang (2011), Daley et al (2009), Tong et al (2012), and Wilson and Weng (2011) find the combined impacts of climate change and development will result in poorer water quality. However, where investigated, climate change impacts were greater than those of land use changes.

Delpla (2009), Carriere et al. (2010), and Emelko (2011) found that changes in physical-chemical-biological parameters and micropollutants will negatively affect drinking water treatment and distribution systems. Wastewater treatment plants will be more vulnerable as increases in rainfall and wet weather lead to higher rates of inflow and infiltration (King County Department of Natural Resources and Parks, 2008; NYCDEP., 2008; Flood and Cahoon, 2011). These plants will also face reduced hydraulic capacities due to higher sea levels and increased river and coastal flooding (Flood and Cahoon, 2011), with higher sea levels also threatening the sewage collection systems (Rosenzweig *et al.*, 2007; King County Department of Natural Resources and Parks, 2008)

26.3.3.3. Flooding

Projected increases in flooding (Georgakakos *et al.*, 2013) may affect sectors ranging from agriculture and livestock in southern tropical Mexico (National Water Commission of Mexico, 2010) to urban and water infrastructure in areas such as Dayton, Ohio, metro Boston and the Californian Bay-Delta region (National Research Council, 1995; Kirshen *et al.*, 2006; California Department of Water Resources, 2009; Wu, 2010). Floods could begin earlier, have earlier peaks and longer durations (e.g., southern Quebec basin . Urbanization can compound the impacts of increased flooding due to climate change, particularly in the absence of flood management infrastructures that take climate change into account (Hejazi and Markus, 2009; Mailhot and Duchesne, 2010; Ntelekos *et al.*, 2010; Sosa-Rodriguez, 2010) estimate that annual riverine flood losses in the USA could increase from approximately $2 billion now to $7-$19 billion annually by 2100 under the business as usual scenario.

26.3.3.4. Instream Uses

Projections of climate impacts on instream uses vary by region and time-frame. Hydropower generation, affected by reduced lake levels, is projected to decrease in arid and semi-arid areas of Mexico (SEMARNAT, 2009; Sosa-Rodriguez, 2013) and in the Great Lakes (Buttle *et al.*, 2004; Mortsch *et al.*, 2006; Georgakakos *et al.*, 2013). In the

US Pacific Northwest it is projected to increase in 2040 by 5% in the winter and decrease by 13% in the summer, with annual reductions of about 2.5%. Larger decreases of 17% to 21% in summer hydropower production are projected by 2080 (Hamlet *et al.*, 2010). On the Peribonka River system in Quebec, annual mean hydropower production would decrease by 1.8% for 2010-2039 and increase by 9.3% and 18.3% respectively during the periods 2040-2069 and 2070-2099 (Minville *et al.*, 2009). Navigation on the Great Lakes, Mississippi River and other inland waterways may benefit from less ice cover but will be hindered by increased floods and droughts (Georgakakos *et al.*, 2013).

26.3.3.5. Energy-Water Nexus

Energy demands for water supply and wastewater treatment are projected to increase under climate change due to increases in pumping and treatment requirements, partly due to increased surface water temperatures (CH2M Hill, 2009; Skaggs *et al.*, 2012). Cooling of USA thermoelectric power plants is predicted to be affected; it accounts for approximately 50% of the nation's water withdrawals (Kenny *et al.*, 2009). The vulnerability of these power plants will vary regionally depending on differences in water availability and temperature due to climate impacts (Wilbanks *et al.*, 2008). Carbon pricing policies may decrease thermoelectric power plant freshwater withdrawals and consumption in the continental USA compared to business as usual policies (Chandel *et al.*, 2011). Total freshwater consumption for national energy production (including thermoelectric power, biofuels, and fossil fuels) in the United States is estimated at 11% (Elcock, 2010; Mekonnen and Hoekstra, 2011; Spang *et al.*, 2013). However, energy production mitigation measures such as carbon capture, nuclear power, and some biofuels will exacerbate stresses on water supplies and quality (Engelhaupt, 2007; Delucchi, 2010; Stone *et al.*, 2010; Powers *et al.*, 2011; Cooper and Sehlke, 2012)

26.3.4. Adaptations

Most of the project-level adaptation actions are no-regret policies. For instance, in preparation for more intense storms, New York City is using green infrastructure to capture rainwater before it can flood the combined sewer system and is elevating boilers and other equipment above ground (Bloomberg, 2012). The Mexican cities of Monterrey, Guadalajara, Mexico City and Tlaxcala are reducing leaks from water systems (SEMARNAT, 2009; National Water Commission of Mexico, 2010; Romero-Lankao, 2010; Sosa-Rodriguez, 2010). Regina, SK has increased urban water conservation efforts (Lemmen *et al.*, 2008).

The 540-foot high, 1300-foot long concrete Ross Dam in the state of Washington, USA was built on a special foundation so it could later be raised in height (Jay Lund, personal communication). Dock owners in the Trent-Severn Waterway in the Great Lakes have moved their docks into deeper water to better manage impacts on shorelines (Coleman *et al.*, 2013). The South Florida Water Management District is assessing the vulnerability to sea level rise of its aging coastal flood control system and exploring adaptation strategies, including a strategy known as forward pumping (Obeysekera *et al.*, 2011). In Cambridge, Ontario, extra capacity culverts are being installed in anticipation of larger runoff (Scheckenberger *et al.*, 2009).

Water meters have been installed to reduce water consumption by different users such as Mexican (also installing drip irrigation) and Canadian farmers and several Canadian cities (INE (National Institute of Ecology), 2006; Lemmen *et al.*, 2008). Agreements and regulations are underway, such as the "shortage sharing agreement" signed in 2007 for the management of the Colorado River, USA and driven by concerns about water conservation, shortage planning, better reservoir coordination, and preserving flexibility to respond to climate change (http://www.usbr.gov/lc/region/programs/strategies.html, accessed January 27, 2013). Quebec Province is also requiring dam safety inspections each 10 years to also account for new knowledge on climate change impacts (http://www.cehq.gouv.qc.ca/loisreglements/barrages/reglement/index-en.htm).

26.4. Ecosystems and Biodiversity

Recent research has documented gradual changes in physiology, phenology and distributions in North American ecosystems (Dumais and Prévost, 2007). Concomitant with 20th century temperature increases, shifts in plant, mammal, bird, lizard, and insect species' distributions have been documented extensively in the western United States and eastern Mexico (Parmesan, 2006; Kelly and Goulden, 2008; Moritz *et al*., 2009; Tingley *et al*., 2009; Sinervo *et al*., 2010). These gradual climate-induced distribution shifts interact with other existing environmental changes such as land-use change, hindering the ability of species to respond.

Different techniques have been applied to assess the vulnerability of North American ecosystems to changes in climate (Loarie *et al*., 2009). A global risk analysis based on dynamic global vegetation models identified boreal forest in Canada as notably vulnerable to ecosystem shift(Scholze *et al*., 2006). Building upon results presented in the AR4, studies have identified a more prominent role of extreme events such as droughts and floods on vegetation mortality, increased infestation by fungi, sea levels rise, hurricanes and other increasingly severe impacts facing North American ecosystems (Chambers *et al*., 2007; IPCC, 2012). Although North American forests were a net carbon sink between 1990-2007 (Pan *et al*., 2011), current measurements suggest a reduction in the global net primary production of 0.55 petagrams of carbon due to large-scale droughts between 2000 to 2009 (Zhao and Running, 2010).

Climatic changes are expected to affect North American terrestrial and coastal ecosystems in significant and in many cases adverse ways. The responses of biological systems depend on organizational level and can differ across communities, populations or species. Changes in temperature, precipitation amount, carbon dioxide concentrations can have differential effects across species and ecological communities (Parmesan, 2006; Matthews *et al*., 2011). Risk studies on 134 species in U.S. and 16 forest species in Mexico estimated shifts in potential habitat under climate scenarios (Iverson *et al*., 2008; Gómez *et al*., 2011; Iverson *et al*., 2012). These studies have contributed to planning management strategies for adaptation of these ecosystems (USDA Forest Service, 2010; Leichenko, 2011; Comisión Intersecretarial de Cambio Climático, 2012).

The following section focuses in more depth on climate vulnerabilities in forests and coastal ecosystems and transboundary ecosystems across all three North American countries where research advances since AR4 justify further exploration. Additional synthesis on climate impacts on ecosystems in general and terrestrial, coastal and ocean in particular can be found in Chapter 8 of the (Groffman *et al*., 2013) and chapters 4, 5 and 6 of AR5.

26.4.1. Tree Mortality and Forest Infestation

26.4.1.1. Observed Impacts

Droughts of unusual severity, extent, and duration have affected large parts of western and southwestern North America and resulted in regional-scale forest dieback in Canada, US and Mexico. Extensive tree mortality has been related to exacerbated drought by higher summertime temperatures mainly in quaking aspen (*Populus tremuloides*), pinyon pine (*Pinus edulis*) and lodgepole pine (*Pinus contorta*) (Breshears *et al*., 2005; Hogg *et al*., 2008; Raffa *et al*., 2008; Worral *et al*., 2008; Michaelian *et al*., 2011; Anderegg *et al*., 2012). Similarly, in 2011 and 2012 oak forest dieback in Northern and central Mexico was associated with extreme temperatures and severe droughts (Conafor, 2012).Widespread forest-mortality events triggered by extreme climate events can alter ecosystem structure, function, and severely impact biodiversity (Phillips *et al*., 2009; Allen *et al*., 2010; Anderegg *et al*., 2013). Similarly, multi-decadal changes in demographic rates, particularly mortality, indicate climate-mediated changes in forest communities over longer periods (Hogg and Bernier, 2005; Williamson *et al*., 2009a). Increases in the average mortality rate of 4.7% yr –1 between 1963 and 2008 were reported for Canada's boreal forests (Peng *et al*., 2011), and in western US forests as well (van Mantgem *et al*., 2009).

The influences of climate change on ecosystem disturbance, such as insect outbreaks have become increasingly salient and suggest that these disturbances could have a major influence on North American ecosystems and

economy in a changing climate. In terms of carbon stores these outbreaks can turn forests into carbon sources (Kurz *et al*., 2008a; Kurz *et al*., 2008b; Hicke *et al*., 2012).

Warm winters in Western Canada and U.S. have allowed the larvae of mountain pine beetle to overwinter, causing the "largest and most severe [outbreak] in history" from Alaska to Colorado (Bentz, 2008), with massive die-offs in some regions. An estimated 18,177 km2 of U.S. forests is affected (Williams *et al*., 2010). British Columbia, Canada had the largest impact (Brown *et al*., 2010a), with mortality in over 7 million hectares (Aukema *et al*., 2006).

26.4.1.2. Projected Impacts and Risks

Projected increases in drought severity in southwestern United States and northwestern Mexico suggest that these ecosystems may be more vulnerable to rapid changes, such as vegetation mortality (Seager *et al*., 2007; Overpeck and Udall, 2010; Williams *et al*., 2010), and an increase of biological agents such as beetles, borers, pathogenic fungi, budworms and other pests (Drake *et al*., 2005). An index of forest drought stress calibrated on tree rings indicates that projected drought stress by the 2050s will exceed the most severe droughts of the past 1,000 years (Park Williams *et al*., 2013).

Major changes are projected towards the end of the century in forest soils in southern Quebec in 2040-2069 and 2070-2099 projected with subsequent decrease between 20-40% in the growing season of trees due to elevated evapotranspiration rates (Houle *et al*., 2012). More frequent droughts in tropical forests may change forest structure and regional distribution, favoring a higher prevalence of deciduous species in the forests of Mexico (Drake *et al*., 2005; Trejo *et al*., 2011).

Shifts in climate are expected to lead to changes in forest infestation, including expansion into higher latitudes and elevations (Bentz *et al*., 2010). Predicted climate warming is expected to have effects on bark beetle population dynamics in the southwestern United States and Northern part of Mexico that may include increases in developmental rates, generations per year, and changes in habitat suitability (Waring *et al*., 2009). As a result, the impacts of *Dendroctonus frontalis* and *Dendroctonus mexicanus* on forest resources are likely subject to amplification (Waring *et al*., 2009).

26.4.2. Coastal Ecosystems

Highly productive estuaries, wetlands and mangrove ecosystems are present in the East and West coasts of North America. These fragile ecosystems are vulnerable to sea level rise, increase in sea surface temperature, acidification of water, and hurricanes. Coastal zones are subject to many other stressors as well, including urban and tourist developments and the indirect effects of overfishing *(*Bhatti, 2006); (Mortsch *et al*., 2006; CONABIO-CONANP-TNC-PRONATURA, 2007; Lund *et al*., 2007)

26.4.2.1. Observed Impacts

Sea level rise, which has not been uniform across the coasts of North America (Crawford *et al*., 2007; Kemp *et al*., 2008; Leonard *et al*., 2009; Zavala-Hidalgo *et al*., 2010; Sallenger *et al*., 2012), is directly related to flooding and loss of coastal dunes, oyster beds, seagrass and mangroves affectations (Feagin *et al*., 2005; Cooper *et al*., 2008; Najjar *et al*., 2010; Martinez Arroyo *et al*., 2011; McKee, 2011). Influenced by rising sea levels, severe flooding and salinity movement inward in deltas have been detected in Sacramento-San Joaquin area, which can severely alter vegetation and species habitat (Lund *et al*., 2007).

Increases in sea surface temperature in estuaries threaten species, especially cold water fish and the metabolism of many organisms (Crawford *et al*., 2007). Historical warm periods have coincided with low salmon abundance and restriction of fisheries in Alaska (Crozier *et al*., 2008; USGCRP, 2009). In addition, some fisheries currently support

sardine fishing where they once fished for anchovy (Chavez *et al*., 2003). North Atlantic mammals, and tropical coral reefs in the Gulf of California, and the Caribbean are affected by increase in transmission diseases associated with warming of waters and low water quality(ICES, 2011; Mumby *et al*., 2011).

There is *very high confidence* about acidification in oceans and coasts (Box CC-OA). The increased CO2 contributes to acidification and affects mainly calcareous organisms colonial mussel beds temperate coastal and indirectly influences food webs of benthic species (Wootton *et al*., 2008). The acidity in conjunction with high temperatures have been identified as a serious threat to coral reefs and other marine ecosystems (Doney *et al*., 2009; Hernández *et al*., 2010; Mumby *et al*., 2011).

The ecological effects of tropical storms and hurricanes can alter coastal wetland hydrology, geomorphology (erosion), biotic structure in reefs and nutrient cycling. Hurricanes impacts on the coastline change dramatically the marine habitat of sea turtles reducing feeding habitats, like coral reefs, areas of seaweed and nesting places. (Liceaga-Correa *et al*., 2010; Márquez, R. and Jiménez, Ma. del C., 2010).

26.4.2.2. Projected Impacts and Risks

Projected increases in sea levels, particularly along the coastlines of Florida, Louisiana, North Carolina, and Texas(Kemp *et al*., 2008; Leonard *et al*., 2009; Weiss *et al*., 2011a), are projected to reduce flood tolerance of many plants in coastal ecosystems and their recovery almost impossible; result in a loss of wetlands and mangroves of between 20% (in Tamaulipas) to 94% (in Veracruz) for the Gulf of Mexico coast by the end of the 21st century (Flores Verdugo *et al*., 2010); and lead to large losses in tidal marshes in San Francisco Bay (Stralberg *et al*., 2011).

Projected impacts of increased water temperatures include contraction of coldwater fish habitat and expansion of warm-water fish habitat, which can increase the presence of invasive species threatening resident populations (Janetos *et al*., 2008). Up to 40 % of Northwest salmon populations may be lost by 2050 due to climate change (Battin *et al*., 2007; Crozier *et al*., 2008). Future restrictions are expected in productivity and abundance at the southern end while doing the opposite at the northern end of their range (Azumaya *et al*., 2007).

The progressive onset of ocean acidification will cause damage and reduction of coral growth with consequent extinctions and declines in biodiversity (Veron *et al*., 2009). Increases of CO2 alter calcification of bivalve and other organisms with shells, oyster larvae reared with levels between 560 to 480ppm were held in Chesapeake Bay and found slower calcification than in the current environmental conditions (Najjar *et al*., 2010).

The projected increase in the frequency of category 4 and 5 storms by the end of the 21st century (Bender *et al*., 2010; Knutson *et al*., 2010) might directly affect the mangroves over a period of at least 25 years and completely change their structure and age (Kovacs *et al*., 2004).

26.4.3. Ecosystems Resilience, Adaptation, and Mitigation

The resilience of the ecosystems to climate change depends on different and context specific factors: the biodiversity and conservation of habitats and food chains (Thompson *et al*., 2010) the interactions between relatively rapid rate of climate change and the land-use changes that can reduce species capacity to adapt or to be resilient (Bhatti et al 2006); (Magrin *et al*., 2007). The uncertain implications of these changes on productivity of fisheries and forestry (ICES, 2011; Okey *et al*., 2012) can force rural and indigenous population (whose economies depend on this resources) to migrate (Perry *et al*., 2010, section 26.6).

Some adaptation measures have been implemented to respond to climate change impacts on ecosystems: increases in plant community composition and biological diversity to reduce Canadian forest infestations (Johnston *et al*., 2010); breeding programs for resistance to diseases and insect pests (Yanchuk and Allard, 2009); selection by forest or fisheries managers of productive activities that are more adapted to new climatic conditions (chapter 4 Canadian Assessment); effective planning and regulations on other human activities such as commercial fishing and mass

tourism(Pratchett *et al*., 2008); for wetlands in the Great Lakes, Canada and coastal areas in San Joaquin and San Francisco, California, enforcement mechanisms for using water regulation technologies and maintain quantity and quality of water bodies (Mortsch *et al*., 2006; Okey *et al*., 2012).Human-assisted migration has been proposed as a potential management option to maintain optimal health and productivity of forests; yet the technique has logistical and feasibility challenges (Keel, 2007; Winder *et al*., 2011).

Adaptation research suggests that improving climate resilience and adaptation requires changes in the approach to protected area planning, establishment and management (CONABIO-CONANP-TNC-PRONATURA, 2007; March *et al*., 2011), and that it will be much more difficult and, in some cases, not sufficient if global temperature rise exceeds 2ºC above preindustrial levels (Mansourian *et al*., 2009). One of the more notable short-term changes in the policy arena is the discussion of GHG emissions reduction through CDM and REDD+ and management, conservation and restoration of forest carbon stocks. There are manifold ways through which forests influence the climate both biogeochemically (e.g. carbon sequestration) and biophysically (e.g. albedo and roughness)(Anderson and Bell, 2009; Anderson *et al*., 2011). Managers face challenges in adjusting management practices in favor of carbon accumulation, while at the same time maintaining biodiversity, recognizing the rights of indigenous people and contributing to local economic development (FAO, 2012).

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Box 26-2. Wildfires

North America's large wildfire activity has markedly increased since the mid-1980s, and large wildfires have occurred with increased frequency and durations, within longer wildfire seasons (Westerling *et al*., 2006; Williamson *et al*., 2009b). The great conflagrations that have occurred in western Canada, the U.S. and Mexico in recent years are related to long and warm spring and summer droughts in those years, particularly when they have been, accompanied by wind events. (Holden *et al*., 2007; CONAFOR, 2011). Legacies of forest management also play a substantial role in wildfire risk across systems.

Socio-Ecological Impacts

Although fire-adapted ecosystems exist, increasing summer wildfires could lead to changes in dominant vegetation types and community structure. In places like Sierra Nevada, mixed conifer forests, which have a natural cycle of small, non-crown fires, will have an increased likelihood of massive crown-fires. Human use of fires in forests not prone to fires, such as tropical forests can have devastating impacts, and is strongly related to the frequency of fires (Bond and Keeley, 2005; CONANP and TNC, 2009).

While healthy forests provide carbon sequestration that benefits climate change mitigation, forests affected by pests and fires are less effective carbon sinks, and wildfires themselves are a source of emissions. Furthermore, fires pose a direct threat to human lives, property and health. The expansion of human habitation or productive activities in peri-urban areas or near forested areas, alongside legacies of forest management, has undoubtedly increased the probability of ignitions, causing severe fires and increasing human exposure (Radeloff *et al*., 2005; Peter *et al*., 2006; Fischlin *et al*., 2007; Theobald and Romme, 2007; Gude *et al*., 2008; Hammer *et al*., 2009). Wildfires pose direct health threats as well. According to the EM-DAT disaster database, over the last 30 years, 155 people were killed in wildfires across North America, including 103 in the United States, 50 in Mexico and 2 in Canada (CRED, 2012). Direct effects include injury and respiratory effects from smoke inhalation, with firefighters at increased risk (Naeher *et al*., 2007; Reisen and Brown, 2009; Reisen *et al*., 2011). Contingent on shifting fire regime, there is *high confidence* that wildfire activity will cause health impacts at the individual and neighborhood levels.

Climate Variability and Extremes

Drought conditions are strongly associated with wildfire occurrence, as dead fuels such as needles and dried stems promote the incidence of firebrands and spot fires (Keeley and Zedler, 2009) (Liu, et al.2012). Drought periods in Alberta and Idaho coincide with large burned areas (Pierce and Meyer, 2008; Kulshreshtha, 2011). Decadal climatic oscillations also contribute to drought conditions, and thus to wildfires. The areas burned in the North American boreal forest and in northwest and central Mexico are strongly related to the dynamics of these large-scale climatic patterns (Macias Fauria and Johnson, 2006; Skinner *et al*., 2006; Villers-Ruíz and Hernández-Lozano, 2007; Macias

Fauria and Johnson, 2008), which are already shifting toward hotter temperatures and longer droughts with the advance of climate change.

Southern and western Canada, Alaska and Mexico have all experienced a trend toward drier conditions since the 1950s (Kunkel *et al*., 2008), and augmented drought conditions are projected for a large proportion of the Western interior, Florida, and Mexico by 2100. Drought index projections and climate change regional models carried out in the USA show increases in the potential for fires, mainly in summer and fall, on the southeast Pacific coast, Northern Plains and the Rocky Mountains (Liu, et al 2012).

Adaptation Strategies

Further research on the relationships between climate and wildfire should include attention to population growth, land-use planning and forest structure as important aspects for adaptation planning. Prescribed fire may be an important tool for managing fire risk in Canada and the US (Hurteau and North, 2010; Wiedinmyer and Hurteau, 2010; Hurteau *et al*., 2011). Managers in the U.S. have encouraged reduction of flammable vegetation around structures with some success (Stewart *et al*., 2006). However, such efforts depend largely on the socio-economic capacity of communities at risk, the extent of resource dependence, community composition, and the risk perceptions, attitudes and beliefs of decision-makers, private property owners, and the public (McFarlane, 2006; Repetto, 2008; Collins and Bolin, 2009; Martin *et al*., 2009; Trainor *et al*., 2009; Brenkert-Smith, 2010).

Forest management also requires stakeholder involvement and investment. The provision of adequate information on smoke, managed fire/fire-use, pest management, and forest thinning is crucial, as is building trust between stakeholders and land managers (Dombeck *et al*., 2004; Flint *et al*., 2008; Chang *et al*., 2009). However, institutional shifts from reliance on historical records toward incorporation of climate forecasting in forest management will also be crucial to developing resilience in these areas (McKenzie *et al*., 2004; Millar *et al*., 2007; Kolden and Brown, 2010).

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26.5. Agriculture and Food Security

Climate change is projected to cause food price increases and declines in caloric availability globally (Nelson *et al*., 2009); and changes in supply and price from diversion of production into biofuels (Searchinger *et al*., 2008; Valero-Gil and Valero, 2008; Liverman and Kapadia, 2010). Canada and the U.S. are relatively food secure, although households living in poverty and unengaged in food production are vulnerable. Mexico has high levels of food insecurity, where food constitutes a higher proportion of household budget (Juarez and Gonzalez, 2010). Indigenous peoples are also sensitive. Because North America is a major exporter (FAO, 2009; Schlenker and Roberts, 2009), shifts in agricultural productivity here may have implications for global food security.

26.5.1. Observed Impacts

There is strong evidence of the climate sensitivity of North American agricultural productivity. Historic increases in crop yield are attributed in part to increasing temperatures in Canada and high precipitation in the U.S. (Pearson *et al*., 2008; Nadler and Bullock, 2011; Sakurai *et al*., 2011), but optimum temperature ranges are narrow for many crops, and in many cases have already been reached (Hatfield *et al*., 2008). Yields of grains, forage, livestock and dairy decline significantly above temperature thresholds (Wolfe *et al*., 2008; Schlenker and Roberts, 2009; Craine *et al*., 2010). Increasing temperatures unless accompanied by increased precipitation result in soil organic content declines (Smith *et al*., 2009; Lin and Zhang, 2012), and increases in salinity (Sabo *et al*., 2010). Climate change affects product quality as well (e.g. coffee (Lin, 2007), wine grapes (Hayhoe *et al*., 2004; Jones *et al*., 2005), wheat (Porter and Semenov, 2005), fruits and nuts (Lobell *et al*., 2006), and cattle forage (Craine *et al*., 2010).

Yield variances over time have been attributed to climate variability (Cabas *et al*., 2010) (Almaraz et al 2008). Events such as drought, extreme heat and storms have also had a notable negative effect on economic returns (Chen and McCarl, 2009; Costello *et al*., 2009) (Swanson, Hiley and Venema 2007), particularly in Mexico, where the

agricultural sector accounted for 80% of weather-related financial losses over the past 20 years (Saldaña-Zorrilla, 2008).

26.5.2. Projected Impacts

Studies project productivity gains in northern regions and where water is not projected to be a limiting factor, due to longer and warmer growing seasons (Hatfield *et al*., 2008; Pearson *et al*., 2008; Costello *et al*., 2009; Wheaton *et al*., 2010; Nadler and Bullock, 2011). Overall, net declines in yields of major crops in North America are projected without adaptation, particularly for grains and perennials, although certain regions and crops may experience gains in the absence of extreme events, and projected yields vary widely by climate model (e.g., Paudel and Hatch, 2012). Yield declines combined with increased production costs would affect the economic health of the industry as well as food prices (Kiely *et al*., 2005), although the effects on profitability are difficult to forecast, and can be expected to be nonlinear. Aggregate profits have been projected to decline by up to 58% by 2099 (CCSM, A2) (Deschenes and Kolstad, 2011) in California's agriculture industry. In northwest Montana, Net Farm Income and average returns per acre are projected to decline by 57% and 24% respectively by 2050 (A1B, B1, A2, CMIP3) (Prato *et al*., 2010).

Among studies projecting yield declines, two factors stand out: exceedance of temperature thresholds and water availability. Projected temperature increases may affect yield negatively as early as 2020, with a growing number of studies indicating sharp declines in several major crops by 2099 (e.g., Schlenker and Roberts, 2009) (Hadley III) (Figure 26-5), and increased inter-annual variability over the next century (Sakurai *et al*., 2011; Urban *et al*., 2012). Projected temperature increases in California would result in declines in wine grape yields, where current conditions are already at temperature optimums (Jones *et al*., 2005), cotton and sunflower, (A2,B1, DAYCENT model) (Lee, de Gryze and Six 2009), and nut-bearing trees (Lobell *et al*., 2006). Even in northern regions, such as Quebec, projected temperature increases are higher than optimum for some major crops (Brassard and Singh, 2008) and result in productivity declines for fruit-bearing trees (Wolfe *et al*., 2008).

[INSERT FIGURE 26-5 HERE
Figure 26-5 Nonlinear relation between temperature and yields. Source: Schlenker, 2009.]

The effect of temperature on yield is moderated by changes in precipitation, projections of which are more variable by region, time frame, and climate model. Increases in precipitation would off-set but not necessarily entirely compensate for temperature-related declines in productivity (Kucharik and Serbin 2008). In regions projected to experience increasing temperatures combined with declining precipitation, declines in yield and quality are more acute (Craine *et al*., 2010; Monterroso Rivas *et al*., 2011a). The direct effects of increasing average temperatures on livestock stress, combined with reduced forage quality, would reduce significantly milk production and weight gain in cattle (Wolfe *et al*., 2008; Hernandez *et al*., 2011).

Agriculture is likely to be affected by soil moisture deficits and declining water availability in the U.S. Western/Southwest, the Western Prairies in Canada, and central and northern Mexico (Pearson *et al*., 2008; Cai *et al*., 2009; USGCRP, 2009; Esqueda *et al*., 2010; Vano *et al*., 2010b; Kulshreshtha, 2011). Current sectoral competition for limited water supplies is likely to become more intense (USGCRP, 2009; MacDonald, 2010a; Vano *et al*., 2010a; Lal *et al*., 2011). In the western U.S. and Canadian Prairies, projected earlier Spring snowmelt and higher proportions of precipitation falling as rain would negatively affect agricultural productivity regardless of precipitation levels, as water availability in Summer and Fall are reduced (Forbes *et al*., 2011); (Schlenker *et al*., 2007)(Kienzle et al 2011).

Projected increases in extreme heat, drought andstorms are other factors with negative effects on productivity (Chen and McCarl, 2009; Kulshreshtha, 2011), even in regions in which beneficial impacts in response to projected changes in average conditions are anticipated (Sushama *et al*., 2010). Projected changes in temperature and precipitation would also affect the prevalence and variety of pests, fungi and diseases (Wolfe *et al*., 2008; Jackson *et al*., 2009); (Wu et al 2011). Weeds are generally more responsive to increasing temperatures and CO_2 fertilization than crops (USGCRP, 2009), and the variety of weeds prevalent for a particular region is projected to change (McDonald *et al*., 2009). Organic producers would be particularly affected (Jackson and Wheeler 2010).

Responsiveness to CO_2 varies by crop, and positive growth response ceases when plants reach a CO_2 saturation point; thus CO_2 fertilization may not compensate for the negative impacts of temperature rise (Hatfield et al 2011). Elevated CO_2 can result in reduced nitrogen and protein content in grains and forage grasses (Brassard and Singh, 2008; Karl *et al*., 2009), and weeds are more responsive to CO_2 than crop species (Wolfe *et al*., 2008; USGCRP, 2009).

A Closer Look at Mexico

While agriculture in Canada and the U.S. is largely commercial, in Mexico it is comprised primarily of subsistence farmers (2.1 million) (Claridades Agropecuarias 2006). The negative effects to productivity of projected changes in climate here may be particularly acute, in part because a large proportion of Mexico's landbase is already marginal for two of the country's major crops: corn and beef (Monterroso-Rivas et al 2011b); (Buechler, 2009). Water deficits for Northwestern Mexico, the primary region of irrigated grain farming, may be substantial due to projected larger temperature increases and reductions in precipitation up to 30% greater than the rest of the country by 2050 (mean of ensemble of 18 models, A2 and A1B)(Magana *et al*., 2012). Irrigation, an important source of mitigation during water deficits, is limited in Mexico (Skoufias *et al*., 2011).

Although projected increases in precipitation may contribute to an overall increase in the productivity of rangeland in some regions (Monterroso Rivas *et al*., 2011b)2011a, the direct effects of temperature on livestock stress is expected to reach the dangerous zone by 2020 and continue to rise in Veracruz (A2 and B2, three GCMs) (Hernandez *et al*., 2011). Reduced frost threat in some regions would enhance corn yields (Conde *et al*., 2006). However, decreases from 6.2% currently to between 3% and 4.3% are projected in the land classified as "suitable" for rain-fed corn production (UKHadley B2) (ECHAM5/MPI A2) by 2050 (Monterroso-Rivas et al 2011b). The distribution of most races of corn is expected to be reduced and some eliminated by 2030 (A2, three climate models) (Ureta et al 2012). Coffee, an economically important crop supporting 500,000 primarily indigenous households (Gonzalez Martinez 2006), is projected to decline 34% by 2020 in Veracruz (Gay *et al*., 2006) and from 265400 ha today to 6000 ha by 2050 in Chiapas (A2a, mean of 15 models) (Schroth *et al*., 2009).

26.5.3. Adaptation

Adaptation can off-set projected declines in yields and capitalize on emerging opportunities. Importantly, adaptation imposes both costs and risks onto producers (Wolfe *et al*., 2008), and in some cases will be insufficient (Boyd and Ibarraran, 2009; Prato *et al*., 2010). Technological improvements can increase yield under normal conditions but do not protect harvests from extreme events (USGCRP, 2009; Wittrock *et al*., 2011). Some adaptation strategies may be economically precluded for low-value crops, or maladaptive for other sectors (depletion of groundwater supplies and increased energy consumption). Strong promotion of capital-intensive adaptation strategies may be beyond the means of smallholders (Mercer et al 2012).

26.5.3.1. Adaptation Options

Coping mechanisms, such as insurance, the purchase of livestock feed during droughts, or increased application of herbicides (Craine *et al*., 2010), may be necessary but insufficient, and certainly not optimal. Consideration of the potential for broad application, co-benefits, and unintended consequences of adaptation options will enhance adaptation planning (Belliveau *et al*., 2006). Planting varieties better suited to future climate conditions has high potential (Bootsma *et al*., 2005; Eakin and Appendini, 2008; Coles and Scott, 2009; Paudel and Hatch, 2012), and has been in use by farmers in the past (Conde *et al*., 2006; Nadler and Bullock, 2011).

Other options have multiple co-benefits. Low- and no-till practices that significantly reduce soil erosion and runoff also protect crops from extreme precipitation (Zhang and Nearing, 2005), retain soil moisture, and reduce greenhouse gas emissions (Suddick *et al*., 2010). Strategies to maintain productivity of grazing lands, such as

planting legumes and weed management, enhance soil carbon sequestration (Follett and Reed, 2010). Shade-producing perennials greatly enhances soil moisture retention (Lin, 2010), and contributes to local cooling (Georgescu *et al*., 2011). Increasing crop diversity, an historic risk management strategy that mediates the impacts of climate and market shocks (Eakin and Appendini, 2008), enhances management flexibility (Chhetri *et al*., 2010), and is more conducive to organic practices, which produce lower greenhouse gas emissions (Jackson and Wheeler 2010).

26.5.3.2. Criteria for Adaptation Observed in Existing Practices

High prices may motivate investments in adaptation(Li *et al*., 2011). However, market forces and technical feasibility alone are unlikely to lead to sectoral-level adaptation (Kulshreshtha, 2011), thus institutional support is key, found to be inadequate in many contexts (Klerkx and Leeuwis, 2009; Jacques *et al*., 2010; Tarnoczi and Berkes, 2010; Brooks and Loevinsohn, 2011; Alam *et al*., 2012; Anderson and McLachlan, 2012)(Bryant *et al*. 2008). Small Mexican farmers face limited access to credit and insurance (Eakin, 2006; Wehbe *et al*., 2008; Saldaña-Zorilla and Sandberg, 2009; Walthall *et al*., 2012). In some sectors we are seeing investments in adaptation. International coffee retailers and non-governmental organizations are engaged in enhancing coffee farmers' adaptive capacity (Schroth *et al*., 2009; Soto-Pinto and Anzueto, 2010).

Other key criteria are access to and quality of information (Tarnoczi and Berkes, 2010; Tarnoczi, 2011; Baumgart-Getz *et al*., 2012; Tambo and Abdoulaye, 2012) and the social networks needed to exchange that information and offer mutual support, particularly stronger ties among producers (Chiffoleau, 2009; Wittrock *et al*., 2011; Baumgart-Getz *et al*., 2012). Social networks may be especially important to the level of awareness and concern farmers hold about climate change, which in turn has motivated adaptation (Sánchez-Cortéz and Chavero 2011)(Eakin *et* al., forthcoming)(Frank *et al*., 2010).

26.6. Human Health

North America has been an important source of research on climate-related health impacts and vulnerability. Large national assessments of climate and health have been carried out in both the US and Canada (see reference to them in section 26.1). These have highlighted the potential for changes in impacts of extreme storm and heat events, air pollution, pollen, and infectious diseases, drawing from a growing NA research base analyzing observed and projected relationships among weather variables, vulnerability factors and health outcomes. The causal pathways leading from climate to health are complex, and can be modified by intervening factors including economic status, pre-existing illness, age, other health risk factors, access to health care, built and natural environments, adaptation actions and others. Human health is an important dimension of adaptation planning at the local level, much of which has so-far focused on warning and response systems to extreme heat events (New York State CAC, 2012).

26.6.1. Observed Impacts

26.6.1.1. Storm-Related Impacts

The magnitude of health impacts of extreme storms depends on the interaction between hazard exposure and characteristics of the affected communities (Keim, 2008). Coastal and other low-lying infrastructure and populations can be vulnerable due to flood-related interruptions in communications, healthcare access, and mobility. Health impacts include direct effects on traumatic death and injury (e.g., drowning; impacts of blowing and falling objects; contact with power wires) as well as indirect, longer-term effects related to contamination of water and soil, vector-borne diseases, respiratory diseases and mental health (Gamble *et al*., 2008). Infectious disease impacts from flooding include creation of breeding sites for vectors (Ivers and Ryan, 2006) and bacterial transmission through contaminated water and food sources causing gastrointestinal disease. Chemical toxins can be mobilized from industrial or contaminated sites (Euripidou and Murray, 2004) . Elevated indoor mold levels associated with flooding of buildings and standing water are identified as risk factors for cough, wheeze and childhood asthma

(Bornehag *et al.*, 2001; Jaakkola *et al.*, 2005). Mental health impacts of extreme storms have received relatively little study to date (Berry *et al.*, 2010). Stress of evacuation, property damage, economic loss, and household disruption are some of the mental health triggers (Weisler *et al.*, 2006; Gamble *et al.*, 2008). In the period of recent warming, i.e., 1970 to 2010, there has been no clear trend in US hurricane deaths, once the singular Katrina event is set aside (National Hurricane Center).

26.6.1.2. Extremes of Temperature

A large body of literature in North America has associated high temperatures with increased mortality and morbidity (e.g., Medina-Ramon and Schwartz, 2007; Anderson and Bell, 2009; Deschenes *et al.*, 2009; Knowlton *et al.*, 2009; O'Neill and Ebi, 2009; Cueva-Luna *et al.*, 2011; Hurtado-Díaz *et al.*, 2011; Romero-Lankao *et al.*, 2012). Extremely cold temperatures have also been associated with increased mortality (Medina-Ramon and Schwartz, 2007) , an effect separate from the seasonal phenomenon of excess winter mortality, which does not appear to be directly related to cold temperatures (Kinney, 2012). Most available NA evidence derives from the US and Canada, though one recent study reported significant heat- and cold-related mortality impacts in Mexico City (McMichael *et al.*, 2008).

26.6.1.3. Air Quality

Ozone and particulate matter (e.g., PM2.5 and PM10) have been associated with adverse health effects in many locations in North America (Romero-Lankao *et al.*, 2013). Weather and climate affect concentrations of air pollution over multiple scales in time and space. Emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorological variables such as temperature, humidity, wind speed and direction, and mixing height (Kinney, 2008). However, long-term trends in anthropogenic air pollution in NA are more influenced by trends in emission from sources than by climate, and to-date, there has been no discernible climate-induced trend in outdoor air quality in NA. Forest fires are an important source of particle emissions in NA, and can lead to increased cardiac and respiratory diseases incidence, as well as direct mortality (Rittmaster *et al.*, 2006; Ebi *et al.*, 2008). The indoor environment also can affect health in many ways, e.g., via penetration of outdoor pollution, emissions or pollutants indoors, moisture-related problems, and transmission of respiratory infections. Indoor moisture leads to mold growth, a problem that is exacerbated in colder regions such as northern NA in the winter. Climate variability and change is *likely* to affect indoor air quality, but with direction and magnitude that remains largely unknown (IOM, 2011).

26.6.1.4. Pollen

Exposure to pollen has been associated with a range of allergic outcomes, including exacerbations of allergic rhinitis (Cakmak *et al.*, 2002; Villeneuve *et al.*, 2006) and asthma (Delfino, 2002). Temperature and precipitation in the months prior to the pollen season affects production of many types of tree and grass pollen (Reiss and Kostic, 1976; Minero *et al.*, 1998; Lo and Levetin, 2007; U.S. EPA, 2008). Ragweed pollen production is responsive to temperatures and concentrations of atmospheric carbon dioxide (Ziska and Caulfield, 2000; Wayne *et al.*, 2002; Ziska *et al.*, 2003; Singer *et al.*, 2005). Because pollen production and release can be affected by temperature, precipitation, and CO_2 concentrations, it is possible that pollen exposure and allergic disease morbidity could change in response to climate change. However, to date, the only evidence for observed climate-related impacts are for the timing of the pollen season. Many studies have indicated that pollen seasons are beginning earlier (Emberlin *et al.*, 2002; Rasmussen, 2002; Clot, 2003; Teranishi *et al.*, 2006; Frei and Gassner, 2008; Levetin and Van, 2008; Ariano *et al.*, 2010). Evidence of an earlier start to the pollen season has recently been reported in the United States; some pollen types, such as ragweed, also have shown an increase in season length (Ariano *et al.*, 2010; Ziska *et al.*, 2011). Research on trends in NA has been hampered by the lack of long-term, consistently collected pollen records (U.S. EPA, 2008).

26.6.1.5. Waterborne Diseases

Waterborne infections are an important source of morbidity and mortality in North America. Commonly reported infectious agents in recent US and Canadian outbreaks include legionella bacterium, the cryptosporidium parasite, campylobacter, and giardia (CDC, 2011), (Séguin 2008). Cholera remains an important agent in Mexico (Greer *et al.*, 2008). Risk of waterborne illness is greater among the poor, infants, elderly, pregnant women, and immunocompromised individuals (Rose *et al.*, 2001; Gamble *et al.*, 2008) . In Mexico City, declining water quality has led to ineffective disinfection of drinking water supplies (Mazari-Hiriart *et al.*, 2005; Sosa-Rodriguez, 2010).

Changes in the temperature and the hydrological cycle can influence the risk of waterborne diseases (Curriero *et al.*, 2001; Greer *et al.*, 2008; Harper *et al.*, 2011). Floods enhance the potential for runoff to carry sediment and pollutants to water supplies (Karl *et al.*, 2009). Disparities in access to treated water were identified as a key determinant of under age-5 morbidity due to water borne illnesses in the central State of Mexico (Jimenez-Moleon and Gomez-Albores, 2011).

26.6.1.6. Vectorborne Diseases

The extent to which climate change has altered, and will alter, the geographic distribution of vectors of infectious disease remains uncertain because of the inherent complexity of the ecological system. Spatial and temporal distribution of disease vectors depend not only on climate factors, but also on land use/change, socio-economic and socio-cultural factors, prioritization of vector control, access to health care and human behavioral responses to perception of disease risk, among other factors (Lafferty, 2009; Wilson, 2009). Although temperature drives important biological processes in these organisms, variability in climate on a daily, seasonal or interannual scale may result in organism adaptation and a shift in geographic range, not necessarily an expansion in range (Lafferty, 2009; Tabachnick, 2010; McGregor, 2011). This shift may alter the incidence of disease depending on host receptiveness and immunity, as well as the ability of the pathogen to evolve so that strains are more effectively and efficiently acquired (Reiter, 2008; Beebe *et al.*, 2009; Rosenthal, 2009; Russell, 2009; Epstein, 2010).

North Americans are currently at risk from a number of vector-borne diseases, including Lyme disease (Ogden *et al.*, 2008; Diuk-Wasser *et al.*, 2010), dengue fever (Jury, 2008; Ramos *et al.*, 2008; Johansson *et al.*, 2009; Degallier *et al.*, 2010; Kolivras, 2010; Lambrechts *et al.*, 2011; Riojas-Rodriguez *et al.*, 2011; Lozano-Fuentes *et al.*, 2012), West Nile virus (Morin and Comrie, 2010; Gong *et al.*, 2011) and Rocky Mountain spotted fever, to name a few. There is increasing risk from invasive vector-borne pathogens, such as chikungunya (Ruiz-Moreno *et al.*, 2012) and Rift Valley fever viruses 8(Greer *et al.*, 2008).

26.6.2. Projected Impacts

Projecting future public health consequences of gradual climate warming is challenging, due in large part to uncertainties in the nature and pace of adaptations that populations and societal infrastructure will undergo in response to long-term climate change (Kinney *et al.*, 2008). Additional uncertainties arise from changes over time in population demographics, economic well-being, and underlying disease risk, as well as in the model-based predictions of future climate and our understanding of the exposure-response relationship for heat-related mortality. However, climate warming will lead to continuing health stresses related to extreme high temperatures, particularly for the northern parts of North America. The health implications of warming winters remain uncertain (Kinney, 2012).

There is a large literature examining future climate influences on outdoor air quality in North America, particularly for ozone (Kunkel *et al.*, 2007; Tao *et al.*, 2007; Holloway *et al.*, 2008; Lin *et al.*, 2008; Nolte *et al.*, 2008; Wu *et al.*, 2008; Avise *et al.*, 2009; Chen *et al.*, 2009; Liao *et al.*, 2009; Racherla and Adams, 2009; Lin *et al.*, 2010; Tai *et al.*, 2010). This work suggests with *medium confidence* that ozone concentrations could increase under future climate change scenarios if emissions of precursors were held constant (Jacob and Winner, 2009a). The literature for PM2.5 is more limited than that for ozone (Liao *et al.*, 2007; Tagaris *et al.*, 2008; Avise *et al.*, 2009; Pye *et al.*, 2009;

Mahmud *et al.*, 2010). Several recent studies have projected future health impacts due to air pollution in a changing climate (Bell *et al.*, 2007; Tagaris *et al.*, 2009; Chang *et al.*, 2010; Tagaris *et al.*, 2010). Using a range of climate/air quality models and scenarios as well as a range of health and demographic projections, Post and colleagues (2012) found that future mortality effects of ozone tended to increase in a changing climate. Similar findings were previously reported for the eastern and northeastern US (Knowlton *et al.*, 2004; Bell *et al.*, 2007). Future changes in seasonal timing of pollen release are *likely*. Another driver of future pollen might be changing patterns of vegetation, which are projected to change in the future.

Regarding clean water supplies, extreme precipitation can overwhelm combined sewer systems and lead to overflow events that can threaten human health (Patz *et al.*, 2008). Conditional on a future increase in such events, we can anticipate increasing risks related to water-borne diseases.

Whether future warmer winters in the United States and Canada will promote transmission of diseases like dengue and malaria is uncertain, in part, because of access to amenities such as screening and air-conditioning that provide barriers to human-vector contact. Socio-economic factors also play important roles in determining risks. Better longitudinal datasets and empirical models are needed to address knowledge gaps in research on climate-sensitive infectious diseases, as well as to provide a better mechanism for weighting the roles of external drivers such as climate change on a macro/micro scale, human-environmental changes on a regional to local scale and extrinsic factors in the transmission of vector-borne infectious diseases (Wilson, 2009; McGregor, 2011).

26.6.3. Adaptation Responses

Early warning and response systems can be developed to build resilience to severe climate-relate events (Ebi, 2011) and protect susceptible populations, which include infants, children, the elderly, individuals with pre-existing diseases, and those living in socially and/or economically disadvantaged conditions (Pinkerton *et al.*, 2012). At the urban and regional level, adaptation planning to build resilience for health systems in the face of changing climate is a growing priority (Kinney *et al.*, 2011).

Adaptation to heat events can occur via physiologic mechanisms, indoor climate control, urban-scale cooling initiatives, and as a result of warning and response systems. Additional research is needed on the extent to which warning systems prevent deaths (Harlan and Ruddell, 2011). Efforts to reduce GHG emissions could provide health co-benefits, including reductions in heat-related and respiratory illnesses (Health Chapter, US National Climate Assessment). Tree planting initiatives in cities are often motivated by climate adaptation goals. Health benefits related to pollen can be promoted by careful species selection.

26.7. Infrastructures and Other Economic Sectors

This section covers the following economic sectors not addressed elsewhere in the chapter: manufacturing, mining, energy, and services and infrastructures (insurance, construction, housing, and transportation). Available research typically focuses on the direct impact of climate on economic activity, although recent studies have begun to assess the indirect impacts resulting from, for example, scarce supplies during droughts or disruption of transportation and other infrastructure services from storms or floods.

There is mounting evidence that many sectors across North America are adapting to the risk of loss and damage from weather perils. The limited literature available largely reports a range of adaptive practices and adaptation responses to experience with extreme events, and only an emerging consideration of proactive adaptation in anticipation of future global warming.

26.7.1. Manufacturing

26.7.1.1. Observed Impacts

There is little literature focused on climate change and manufacturing, although one study suggested that manufacturing is among the most sensitive sectors to weather in the United States (Lazo *et al.*, 2011). Weather affects, for example, the supply of raw material (e.g. agricultural inputs for food manufacturing), the production process (e.g. water availability and energy demands for cooling/heating), the transportation of goods (e.g. storm delays can close roads and affect travel time), and the demand for certain products. In 2011, automobile manufacturers in North America experienced production losses associated with shortages of components due to flooding in Thailand (Newswire, 2011). In 2013, reduced cattle-supply and higher feed prices associated with several years of drought in Texas led to a decision to close a beef processing plant (Beef Today Editors, 2013). Other major storms, like Hurricanes Sandy, Katrina and Andrew, significantly disrupted manufacturing activity across North America This included delays in production when plants were forced to shutdown due to direct damages and/or loss of electricity and supply disruptions due to unavailability of parts, as well as difficulties delivering products associated with compromised transportation networks. (Baade *et al.*, 2007; Dolfman *et al.*, 2007).

26.7.1.2. Projected Impacts

The drier conditions projected for many regions of North America (Sun *et al.*, 2008; Seager and Vecchi, 2010a; Wehner *et al.*, 2011) would present challenges, especially for manufacturers located in regions already experiencing water stress. This could lead to increased conflicts over water between sectors and regions, and affect the ability of regions to attract new facilities or retain existing manufacturing operations. A modeling study which considered the impact of projected changes in precipitation on 70 industries in the United States between 2010 and 2050 suggested the potential for losses in production and employment due to declines in water availability and the interconnected nature of different industries (Backus *et al.*, 2013). For instance, costs incurred by chemical companies responding to water deficits could translate to reduced supply or higher costs of chemical products needed by other industries, such as construction, textiles and agriculture (Backus *et al.*, 2013). Declining water levels in the Great Lakes would increase shipping costs by restricting vessel drafts and reducing vessel cargo volume (Millerd, 2011).

For manufacturers dependent on raw materials from mining, the impacts on transportation (*see* section 26.7.5.2) could be high. Another potential concern for manufacturing relates to impacts of heat on worker safety and productivity. Several studies suggest that higher temperatures and humidity would lead to decreased productivity and increased health risks (e.g., Kjellstrom *et al.*, 2009; Hanna *et al.*, 2011; Kjellstrom and Crowe, 2011).

26.7.1.3. Adaptation

There is evidence that some companies are beginning to recognize the risks climate change presents to their manufacturing operations, and consider strategies to build resilience to these risks (National Round Table on the Environment and the Economy, 2012). Air conditioning is a viable and effective adaptation option to address some of the impacts of warming across much of North America, though it does incur additional costs (Scott *et al.*, 2008a). Coca Cola has a water stewardship strategy focusing, among other things, on improving water use efficiency at its manufacturing plants, while Rio Tinto Alcan is assessing climate change risks for their operations and infrastructure, which include vulnerability of transport systems, increased maintenance costs, and disruptions due to extreme events (National Round Table on the Environment and the Economy, 2012 (National Round Table on the Environment and the Economy, 2012).

26.7.2. Mining

26.7.2.1. Observed Impacts

Climatic sensitivities of mining activities (including exploration, extraction, processing, operations, transportation and site remediation) have been noted in the limited literature (Chiotti and Lavender, 2008; Furgal and Prowse, 2008; Meza-Figueroa *et al*., 2009; Ford *et al*., 2010; Gómez-álvarez *et al*., 2011; Kirchner *et al*., 2011; Locke *et al*., 2011; Pearce *et al*., 2011; Stratos Inc, 2011). Drought-like conditions have affected the mining sector by limiting water supply for operations (Pearce *et al*., 2011), enhancing dust emissions from quarries (Pearce *et al*., 2011) and increasing concentrations of heavy metals in sediments (Gómez-álvarez *et al*., 2011). Heavy precipitation events have caused untreated mining wastewater to be flushed into river systems (Pearce *et al*., 2011). High loads of contamination (metals, sulfate and acid) at three mine sites in the United States were measured during rainstorm events following dry periods (Nordstrom, 2009).

26.7.2.2. Projected Impacts

An increase in heavy precipitation events and more intense and/or frequent droughts projected for much of North America is likely to affect mining (Warren and Egginton, 2008; Nordstrom, 2009; Gutzler and Robbins, 2011). Although climate change is perceived as an emerging risk, and in some cases, a potential opportunity by Canadian mine practitioners (Ford *et al*., 2010; Ford *et al*., 2011; Pearce *et al*., 2011; National Round Table on the Environment and the Economy, 2012), potential impacts on transportation are perceived as a key issue for Canadian mines (Ford *et al*., 2011), as is limited water availability (Acclimatise, 2009) from projected drier conditions (Sun *et al*., 2008; Seager and Vecchi, 2010a).

A study on acid rock damage drainage in Canada concluded that while the mining sector could minimize the impacts of incremental change to 2050, an increase in heavy precipitation events presented a greater risk of both environmental impacts and economic costs (Stratos Inc, 2011) Climate change impacts that affect the bottom-line of mining companies (through direct impacts or associated costs of adaptation), would have consequences for employment, for both the mining sectors and local support industries (Backus *et al*., 2013).

26.7.2.3. Adaptation

Despite awareness of the potential role of adaptation within the mining industry, there is presently little evidence of proactive adaptation planning within the mining sector (Acclimatise, 2009; Ford *et al*., 2010; Ford *et al*., 2011). However, adjustments to management practices to deal with short-term water shortages, including reducing water intake, increasing water recycling and establishing infrastructure to move water from tailing ponds, pits and quarries, have worked successfully in the past (Chiotti and Lavender, 2008). Climate change is now considered in the design phase of mines in Canada, as a requirement of the Canadian environmental assessment process (Prowse *et al*., 2009). Integrating climate change considerations at the mine planning and design phase increases the opportunity for effective and cost-efficient adaptation (Stratos Inc, 2011).

26.7.3. Energy

26.7.3.1. Observed Impacts

The energy is particularly sensitive to climate change though literature is unequally distributed among countries. Across the United States, energy demand for cooling has increased over the last 40 years, while demand for heating has decreased.(Dell et al.) (2013), note that recent extreme weather events such as hurricanes have disrupted energy production and distribution.

26.7.3.2. Projected Impacts

In Canada, a net decrease in annual energy demand is projected by 2050 and by 2100 (Isaac and Van Vuuren, 2009). The net change in United States energy demand by 2080 is estimated to range from -15 to +4% (Wilbanks *et al.*, 2008), , with peak demand for electricity increasing more than the average demand for electricity, and capacity expansion required in many areas.

Rising temperatures (which reduce thermal power plant efficiencies) and limited water supplies (which affect power plant cooling) are projected to affect both energy production and hydropower and renewable energy sources. Changing cloud cover affects solar energy resources, changes in winds affect wind power potentials, and temperature change and water availability can affect biomass production (for instance, water requirements for biofuel production) (Wilbanks *et al.*, 2008).

The magnitude of projected impacts on hydropower potential will vary significantly between regions and within drainage basins, as flow regimes shift in response to changing climate (Desrochers *et al.*, 2009; Kienzle *et al.*, 2012; Shrestha *et al.*, 2012). Annual mean hydropower production in the St. Lawrence and Great Lakes region of Canada is estimated to decrease by 1.8% in the period 2010–2039 and then increase by 9.3% and 18.3% during the periods 2040–2069 and 2070–2099, respectively (Minville *et al.*, 2009). Regionally in the United States, major concerns include effects of increased cooling demands and water scarcity in the west; effects of extreme weather events, sea-level rise, and seasonal droughts in the southeast; effects of increased cooling demands in the northern regions; effects of warming on energy production and transportation in Alaska; and effects of climate policy on regions whose economies are closely tied to fossil energy production and conversion (Wilbanks *et al.*, 2008).

26.7.4. Insurance

26.7.4.1. Observed Impacts

Property insurance and reinsurance companies across North America experienced a significant increase in severe weather damage claims paid over the past three or four decades(Cutter and Emrich, 2005; Bresch and Spiegel, 2011; Munich Re, 2011). Most of the increase in insurance costs has been attributed to increasing exposure of people and assets in areas of risk (Pielke Jr *et al.*, 2008; Barthel and Neumayer, 2012). A role for climate change has not been excluded, but the increase to date in damage claims is largely due to growth in wealth and population(Field *et al.*, 2012).

Severe weather and climate risks have emerged over the past decade as the leading cost for property insurers across North America, resulting in significant change in industry practices. The price of insurance increased in regions where the risk of loss and damage has increased, and discounts were introduced where risks have been reduced.

26.7.4.2. Projected Impacts

Without adaptation, there is an expectation that severe weather insurance damage claims will increase significantly over the next several decades across North America (World Bank, 2010). The risk of damage is expected to rise due to continuing growth in wealth, the population living at risk, and climate change. There is also an expectation that some weather perils in North America will increase in severity, including Atlantic hurricanes and the area burned by wildfire (Karl *et al.*, 2008), and frequency, including intense rainfall events (Field *et al.*, 2012).

26.7.4.3. Adaptation

Most adaptation in the insurance industry, one of the most studied sectors with respect to adaptation to present and future weather and climate impacts (Mills and Lecomte, 2006; Mills, 2007; Mills, 2009; Autorite des Marches

Financiers, 2011; Leurig, 2011), has been in response to an increase in severe weather damage, with little evidence of proactive adaptation in anticipation of future climate change.

Catastrophe models were developed to help insurers manage the risk of insolvency, their capital needs and the appropriate use of reinsurance. In addition to pricing decisions based on an actuarial analysis of historic loss experience, many insurance companies now use model information to help determine the prices they charge and discounts they offer. Most insurance companies have established specialized claims handling procedures for responding to catastrophic events (Kovacs, 2005; Mills, 2009).

A recent Bank of International Settlements study of more than 2,000 major catastrophes since 1960 found that insurance is a critical adaptive tool available to help society minimize the adverse economic consequences of natural disasters. In the United States and Canada homeowners make extensive use of insurance to manage a broad range of risks, and those with insurance recover quickly following most extreme weather events. However the majority of public infrastructure is not insured and it frequently takes more than a decade before government services fully recover. In contrast Mexico has a well-developed program for financing the rebuilding of public infrastructure following a disaster (FONDEN) but insurance markets are only beginning to emerge for homeowners and businesses. (In 2010, per capita spending on property and casualty insurance was US$2,112.80 in the United States, US$1,870.60 in Canada and US$92.90 in Mexico (Bevere *et al*., 2012).)
Insurance companies are also working to influence the behavior of their policyholders to reduce the risk of damage from climate extremes (Kovacs, 2005; Anderson *et al*., 2006; Mills, 2009). For example, the industry supports the work of the Insurance Institute for Business and Home Safety in the United States, and the Institute for Catastrophic Loss Reduction in Canada working to champion change in the building code and communicate to property owners, governments and other stakeholders best practices for reducing the risk of damage from hurricanes, tornadoes, winter storms, wildfire, flood and other extremes.

26.7.5. Other Service Industries

Most service industries are less climate-sensitive than goods-producing industries, except insurance and tourism (Ford *et al*., 2010; Ford *et al*., 2011). Three broad categories of impacts of climate extremes can affect tourism destinations, competitiveness, and sustainability. The first relates to direct impacts on hotels, access roads and other tourist infrastructures; on such operating costs as heating/cooling, snowmaking, irrigation, food and water supply, evacuation, and insurance; on emergency preparedness requirements; and on business disruption (e.g., sun-and-sea or winter sports holidays). The second category refers to indirect environmental change impacts of extreme events on biodiversity and landscape change (e.g., coastal erosion), which may negatively affect the quality and attractiveness of tourism destinations. Particular tourist regions can suffer as a result of tourism-adverse perception after occurrence of the extreme event itself (Scott *et al*., 2008a).

26.7.5.1. Construction and Housing

26.7.5.1.1. Observed impacts

The risk of damage from climate perils is a significant issue for the housing and construction industries, though little research has systematically explored the topic (Morton *et al*., 2011).
There are no public sources of data that track damage to the built environment from weather events in North America. Private data from insurance companies report a significant increase in severe weather damage to buildings and other insured infrastructure over several decades. Studies indicate that the increase in reported damage is largely due to rising wealth and populations living at risk.

26.7.5.1.2. Projected impacts

Most studies project a significant further increase in damage to homes, buildings and infrastructure. Affordable adaptation in design and construction practices could reduce much of the risk of climate damage for new buildings and infrastructure, likely involving reform in Building Codes and other standards. However, adaptation best practices in design and construction are often prohibitively expensive to apply to existing buildings and infrastructure, so much of the projected increase in climate damage risk involves existing buildings and infrastructure.

26.7.5.1.3. Adaptation

Engineering and construction knowledge exists to design and construct new buildings to accommodate the risk of damage from historic extremes and anticipated changes in severe weather (Kelly, 2010; Ministry of Municipal Affairs and Housing, 2011; Institute for Business and Home Safety, 2012). Older buildings may be retrofit to increase resilience, but these changes are often more expensive to introduce into an existing structure than if they were included during initial construction.

The housing and construction industries have made advances toward climate change mitigation by incorporating energy efficiency in building design (Heap, 2007). Less progress has been made in addressing the risk of damage from extreme weather events (Kenter, 2010). In some markets, like the Gulf Coast of the United States, change is under way in the design and construction of new homes in reaction to recent hurricanes, but in most markets across North America there has been little change in building practices. The cost of adaptation measures combined with limited long-term liability for future buildings influenced some builders to take a wait-and-see attitude (Morton *et al.*, 2011). Exploratory work is under way to consider implementation of building codes that would focus on historic weather experience and also introduce expected future weather risks (Auld *et al.*, 2010; Ontario Ministry of Environment, 2011).

26.7.5.2. Transportation

26.7.5.2.1. Observed impacts

Transportation infrastructure across North America is aging, or inadequate (Mexico) which may make it more vulnerable to damage from extreme events, like intense rainfall washing away roads or rails, and slow onset perils like sea level rise and melting permafrost. The American Society for Civil Engineers estimates that more than US$2 trillion is needed to bring infrastructure in the United States up to “good condition” (ASCE, 2009, p.6). The U.S. Department of Transportation estimated that between US$100 and US$175 billion would be needed in the next 20 years to upgrade U.S. highways (Federal Transit Administration, 2008). Canadian infrastructure had an investment deficit of C$125 billion in the 1980s and 1990s (Mirza and Haider, 2003).

26.7.5.2.2. Projected impacts

Scholarship on projected climate impacts on transportation infrastructure focuses mostly on US and Canada. The Transportation Research Board found that increases in high temperature events, intense precipitation, drought, sea level, and storm surge could affect transportation across the United States. The greatest risks would be to coastal transportation infrastructure, but there could be benefits to marine and lake transportation in high latitudes from shorter period with ice cover (Transportation Research Board, 2008). A one meter sea level rise combined with a 7 meter storm surge could inundate over half of the highways, arterials, and rail lines in the United States Gulf coast (Savonis *et al.*, 2008). While in southern Canada by the 2050s, low temperature cracking from either the B2 or A2 scenarios would decrease, structures would freeze later and thaw earlier, and higher extreme temperatures would increase the potential for rutting (Mills *et al.*, 2009) and related maintenance and rehabilitation costs (Canadian Council of Professional Engineers, 2008).

A 1 to 1.5°C increase in global mean temperature would increase the costs of keeping paved and unpaved roads in the United States in service by, respectively, US$1.9 to US$2.8 billion per year by 2050 (Chinowsky *et al.*, Submitted). Up to 100,000 bridges in the United States crossing rivers and streams could be made vulnerable by increasing peak flows in the mid- and late-21st Century under the A1B and A2 scenarios. Currently deficient bridges, about one-fourth of the current bridges, would be most vulnerable. Strengthening the vulnerable bridges to be more resilient to climate change is estimated to cost US$138 to US$247 billion, but the costs could be reduced by 27 to 28% if currently deficient bridges are strengthened (Wright *et al.*, 2012).

26.8. Urban and Rural Settlements

26.8.1. Weather and Climate Impacts

Observed impacts in North American settlements such as livelihood stresses and changes in access to essential services have been attributed, *with different degrees of certainty,* to climate variability and change including but not limited to: changes in mean climate conditions (SLR, temperature and precipitation) and in extreme events.

26.8.1.1. Changes in Mean Conditions

In coastal zones, SLR and storm surges have reduced development options and increased hazard risk. This process was observed dramatically in New York in 2012, but it is also affecting other settlements along the mid-Atlantic, the Gulf of Mexico, and the St. Lawrence (Kirshen *et al.*, 2008; Friesinger and Bernatchez, 2010; Zavala-Hidalgo *et al.*, 2010; Rosenzweig *et al.*, 2011; Tebaldi *et al.*, 2012).

During the 20th century temperatures increased faster in cities compared to rural areas, due mainly to the urban heat island (UHI) (Harlan and Ruddell, 2011) resulting from land and energy use patterns.

26.8.1.2. Extreme Events

Droughts are among the more notable extreme events affecting North American settlements recently, with severe occurrences in the Canadian Prairies (2001-2) (Wheaton *et al.*, 2007) and Southwestern US - Northern Mexico (2010-2012)—argued to be the most severe in a century (MacDonald, 2010a). The 2012 drought affected 80% of agricultural land in the U.S., with 2,000 counties designated disaster zones by September (USDA Economic Research Service, 2012), http://www.ers.usda.gov/topics/in-the-news/us-drought-2012-farm-and-food-impacts.aspx, accessed November 25, 2012). Road pavement in Chicago buckled under temperatures over 100oF (CBS Chicago, 2012). In Colorado two wildfires burned over 600 homes (NCDC (National Climate Data Center), 2013). Among the most severely affected were indigenous peoples, such as the Rarámuri of Chihuahua (Imison, 2012)

Pest outbreaks such as the Mountain Pine Beetle infestation that emerged across western North America early in the 21st Century, describe another significant recent event attributed to climate change, affecting rural and peri-urban settlements (Kurz *et al.*, 2008a). *Wildfires* have also had notable effects (Box 26-2).

Extreme storms have also had their effect, although changes in their frequency are difficult to attribute to anthropogenic climate change. While immediate health and safety threats associated with such events have been minimized in most cases, impacts on the built environment have been costly. Heavy precipitation, storm surges, flash-floods and wind have compromised homes and business (Comfort, 2006; Kirshen *et al.*, 2008; Jonkman *et al.*, 2009; Romero-Lankao, 2010), including flooding in the U.S. Midwest (2011), and hurricanes in southern Mexico (2004-5). Hurricane Wilma alone caused $1.8 billion in damage, among the biggest insurance losses in Latin American history (Galindo *et al.*, 2009).

Lives and livelihoods have been affected by extreme events. Examples include:

- A relationship between heat and excess mortality in cities, with city-specific thresholds varying with latitude and hazard magnitude (O'Neill and Ebi, 2009; Romero-Lankao *et al*., 2012).
- The Canadian forest sector has shed 100,000 jobs since 2005, attributed in part to the mountain pine beetle (Parkins and MacKendrick, 2007; Parkins, 2008; Holmes, 2010; MacKendrick and Parkins) identified 30 communities and 25,000 families in British Columbia directly affected.
- Observed shifts in Pacific Northwest marine ecosystems attributed to climate change have restricted fisheries; northeast fisheries are projected to follow suit (USGCRP, 2009).
- Loss of 3.2 million tons of maize placing 2.5 million Mexicans at risk of food insecurity (DGCS, 2012), http://www.dgcs.unam.mx/boletin/bdboletin/2012_053.html, accessed November 25, 2012).
- Drought-related economic and employment losses in the Canadian Prairies (Wheaton *et al*., 2007; Kulshreshtha, 2011).
- Intensified inequalities in vulnerability to wildfire between amenity migrants and low-income residents in peri-urban areas (Collins and Bolin, 2009).

Human settlements are differentially affected by impacts to ecological services. Among the most essential human services, changes in water supplies have immediate implications for economies and health (section 26.3).

26.8.2. Observed Factors and Processes Associated with Vulnerability

Differences in severity of climate impacts are strongly influenced by context-specific factors and processes exacerbating or ameliorating vulnerability (Table 26-1; Cutter *et al*., 2013), each of which is more pertinent to some types of settlements than others. Human settlements simultaneously face a multilevel array of non-climate-related risks (e.g., economic, industrial, technological) that contribute to climate change vulnerability (McGranahan *et al*., 2007; Satterthwaite *et al*., 2007; Romero-Lankao and Dodman, 2011). In the following we highlight key sources of vulnerability for urban and rural systems.

[INSERT TABLE 26-1 HERE
Table 26-1: Dimensions of vulnerability. Source: Romero-Lanka, 2012.]

26.8.2.1. Urban Settlements

Geography: The concentration of populations, economic activities, cultural amenities and built environments characteristic of urban areas in highly-exposed locations such as coastal and arid areas creates hazard risks. Of particular concern are Canadian prairie cities; US-Mexico border cities; major U.S. urban areas including Boston, New York, Chicago, Washington, DC, Los Angeles, and Mexico City (Bin *et al*., 2007; Collins, 2008; Kirshen *et al*., 2008; Collins and Bolin, 2009; Gallivan *et al*., 2009; Hayhoe *et al*., 2010; Romero-Lankao, 2010; Rosenzweig *et al*., 2010; Wittrock *et al*., 2011). Without effective policies, environmental impacts such as poor urban air quality can exacerbate climate impacts (Romero-Lankao *et al*., 2013).

Interactive causes and effects: As with all complex systems, the interaction of multiple processes (e.g., disaster management, economic stratification, high-magnitude hazards) can contribute to urban vulnerability. Research increasingly emphasizes the interrelated nature of economic, social and ecological impacts (Gasper *et al*., 2011). For instance, under current local financial constraints, climate-related economic losses can reduce resources available to address social issues, thus threatening institutional capacity and urban livelihoods (Kundzewicz *et al*., 2008).

Urbanization changes land-use and land-surface physical characteristics (e.g., surface albedo, Chen *et al*., 2011). A 34% increase in U.S. urban land development (Alig *et al*., 2004) between 1982 and 1997 had implications for water supplies and extreme event impacts. Effects on water are of special concern, as urbanization can enhance or reduce precipitation, depending on climate regime, geographical location and regional patterns of land, energy and water use (Cuo *et al*., 2009). Urbanization also has significant impacts on flood climatology through atmospheric processes tied to the Urban Heat Island (UHI), the Urban Canopy Layer (UCL), and aerosol composition of airsheds

(Ntelekos *et al*., 2010) . The UHI, which varies across and within cities (Harlan *et al*., 2008; Miao *et al*., 2011), can increase health risks (health section).

Urbanization imposes path dependencies that can amplify or attenuate vulnerability (Romero Lankao and Qin, 2011). For example, the overexploitation of Mexico City's aquifer by 19.1 - 22.2 m^3/s has reduced groundwater levels and caused subsidence, undermining building foundations and infrastructure and increasing residents' vulnerability to earthquakes and heavy rains (Romero-Lankao, 2010).

The Built Environment: Housing stock, urban form, condition of water and power infrastructures, and changes in urban and ecological services also affect vulnerability. Large, impermeable surfaces and buildings disrupt drainage channels and accelerate run-off (Walsh *et al*., 2005). Damage from floods can be much more catastrophic if drainage or waste collection systems are inadequate to accommodate peak flows (Richardson, 2010; Sosa-Rodriguez, 2010). While infrastructures in many Canadian and US cities are in need of adaptation upgrades (Doyle *et al*., 2008; Conrad, 2010), Mexican cites are additionally faced with infrastructure deficits (Niven *et al*., 2010; Hardoy and Romero Lankao, 2011), and high levels of socio-spatial segregation (Smolka and Larangeira, 2008).

Institutional capacity: Although cities have comparatively higher revenue pools than rural municipalities, barriers to urban adaptation planning persist, including fragmented governance, asymmetries in information access and communication, fiscal constraints to support public services including emergency personnel, and top-down decision making (Carmin *et al*., 2012b; Romero-Lankao *et al*., 2013).

Differences in human and social capital: Cities are better endowed than rural populations with individual and neighborhood assets such as income, education, quality of housing and access to infrastructures and services that offer protection from climate hazards. However, socio-spatial differences in access shape response capacities (Harlan and Ruddell, 2011; Romero-Lankao *et al*., 2013). Social networks, family bonds and other forms of social capital differentially influence individual-level vulnerability (Romero-Lankao *et al*., 2012).

Economic Sensitivity: Climate hazards affect the economic activities and highly-valued physical capital of cities (real estate, transportation infrastructure); some urban areas are particularly exposed to key resource constraints (e.g., water in the US-Mexico Border); others are dependent upon climate-sensitive sectors (e.g., tourism) (Lal *et al*., 2011). Disruptions to production, services and livelihoods, and changes in the costs of raw materials and inputs also impact the economic performance of cities (Hunt and Watkiss, 2011).

Risk Distribution: Class and socio-spatial segregation are key determinants vulnerability. Economic elites are better positioned to access the best land and enjoy the rewards of environmental amenities such as clean air, safe drinking water, open space, and tree shade (Morello-Frosch *et al*., 2002; Harlan *et al*., 2006; Harlan *et al*., 2008; Ruddell *et al*., 2009). Although wealthy sectors are moving into risk prone coastal and forested areas (Collins, 2008), and certain hazards (air pollution) affect both rich and poor alike (Romero-Lankao *et al*., 2013), climate risks tend to be disproportionally borne by the poor or otherwise marginalized populations (Cutter *et al*., 2008; Collins and Bolin, 2009; Romero-Lankao, 2010; Wittrock *et al*., 2011). Marginalized populations are moving to peri-urban areas with inadequate services, a portfolio of precarious livelihood mechanisms, and inappropriate risk-management institutions (Collins and Bolin, 2009; Eakin *et al*., 2010; Monkkonen, 2011; Romero-Lankao *et al*., 2012); (Colton, 2008).

26.8.2.2. Rural Settlements

Geography: Geographic isolation can be a key source of vulnerability, for rural communities, with long commutes to essential services like hospitals, and non-redundant transportation corridors that can be compromised during extreme events (Chouinard *et al*., 2008). Many Indigenous communities are isolated, raising the costs and limiting the diversity of imported food, fuel and other supplies, rendering the ability to engage in subsistence harvesting especially critical for wellbeing (Andrachuk and Pearce, 2010; Hardess *et al*., 2011).

Interactive causes and effects: The legacy of previous and current stresses contributing to rapid population growth or loss, reduced employment, or degradation of local knowledge systems, can increase vulnerability (Brklacich *et al*., 2008; Coles and Scott, 2009; McLeman, 2010). Engagement in export markets presents opportunity but also exposure to economic volatility (Eakin, 2006; Saldaña-Zorilla and Sandberg, 2009), and economic downturns take attention away from climate change adaptation. Many indigenous peoples maintain strong cultural attachment to ancestral lands, and thus are especially sensitive to declines in the ability of that land to sustain their livelihoods and cultural wellbeing (Downing and Cuerrier, 2011).

The Built Environment: Rural physical infrastructure is often inadequate to meet service needs or is in poor condition (McLeman and Gilbert, 2008; Krishnamurthy *et al*., 2011), especially for Indigenous communities (section 26.9, Brklacich *et al*., 2008; Hardess *et al*., 2011; Lal *et al*., 2011). The lack of redundant power and communication services compromises hazard response capacity.

Economic Sensitivity: Rural economies have less diversity, and higher dependence on climate-sensitive sectors (Johnston *et al*., 2008; Lemmen *et al*., 2008; Molnar, 2010), and are sensitive to climate-induced reductions in resource supply and productivity, in addition to direct exposure to climate hazards (Daw *et al*., 2009). Single-sector economic dependence contributes significantly to vulnerability (Cutter *et al*., 2003). Farming and fishing provide both economic and food security, the impacts of climate thus posing a double threat to livelihood (Badjek *et al*., 2010), particularly among women (Bee *et al*., 2013). Inter-related factors affecting vulnerability in forestry and fishing communities include over-harvesting, and the cumulative environmental effects of multiple land use activities (Brklacich *et al*., 2008). Many tourism-based communities are dominated by low-wage, service-based employment (Tufts, 2010), and small businesses that lack resources for emergency planning (Hystad and Keller, 2006; Hystad and Keller, 2008). Non-renewable resource industries are sensitive to power and water supply and transportation disruptions associated with hazards.

Institutional capacity: Small revenue pools translate into fiscal constraints necessary to support public services, including emergency personnel and health care (Lal *et al*., 2011).

Differences in human capital and social capital: North American rural communities have a higher proportion of lower income and unemployed populations and higher poverty than cities (Whitener and Parker, 2007; Lal *et al*., 2011; Skoufias *et al*., 2011). 55% of Mexico's rural residents live in poverty, and the livelihood of 72% of these is in farming (Saldaña-Zorrilla, 2008). U.S. and Canadian rural communities have older populations (McLeman, 2010) and lower education levels (Lal *et al*., 2011). Indigenous communities have lower education levels, and high levels of poverty, but are younger than average populations (Downing and Cuerrier, 2011). The legacy of their colonial history, furthermore, has stripped Indigenous communities of many sources of social and human capital (Brklacich *et al*., 2008; Hardess *et al*., 2011).

Conversely, rural and indigenous community members espouse valuable local and experiential knowledge regarding regional ecosystem services (Nakashima *et al*., 2011).

26.8.3. Projected Climate Impacts on Human Settlements

Urbanization, migration, economic disparity, and institutional capacity are likely to influence future impacts and adaptation to climate change in North America.

Projected SLR is *very likely* to alter regional land development differentially, depending on regional shifts in ocean circulation (U.S. GAO, 2007; Yin *et al*., 2009; Conrad, 2010; Sobel *et al*., 2010; Millerd, 2011), making some areas particularly vulnerable to inundation (Cooper and Sehlke, 2012). SLR also exacerbates vulnerability to extreme events such as hurricanes(Frazier *et al*., 2010).

Temperatures increases are *very likely* lead to additional health hazards in cities. Baseline warmer temperatures in cities are expected to be further elevated by extreme heat events whose intensity and frequency is projected to increase during the 21st century (section 26.2) and impair the health of urban populations (section 26.6), particularly

in northern mid-latitude cities (Jacob and Winner, 2009b). Participation in outdoor activities would also increase as a result of projected increases in warm days (Scott and McBoyle, 2007); winter sports face shorter seasons. Projected snowfall declines Canada and the Northeast U.S. would reduce length of winter sport seasons (McBoyle *et al.*, 2007; Scott *et al.*, 2008b).

Extreme Events, such as intense precipitation, flooding and prolonged dry periods are *likely* to affect settlements on coasts, flood-prone deltas and arid regions (Kirshen *et al.*, 2008; Nicholls *et al.*, 2008; Richardson, 2010; Weiss *et al.*, 2011b). Using an operational hurricane-prediction model (NOAA-GFDL) Bender et al. (2010) project an almost doubling in frequency of category 4 and 5 hurricanes by 2100. By the end of this century, New York City is projected to experience nearly twice as many extreme precipitation days compared to today (A2, mean ensemble of 17 models, (Cayan *et al.*, 2010; Ntelekos *et al.*, 2010) project increased number and duration of droughts in the southwest U.S., with most droughts expected to last over five years by 2050 (GDFL CM2.1 and CNRM CM3, A2 and B1). Wildfire vulnerability in the southwest has been elevated with peri-urban growth (Collins and Bolin, 2009; Brenkert-Smith, 2010) .

Climate impacts on *Lives and Livelihoods* have been relatively less studied. Projected shifts in forest productivity indicate potential substantial shifts in livelihood options without adaptation. Sohngen and Sedjo (2005) estimate losses from climate change in the Canadian/U.S. timber sector of $1.4 – $2.1 billion per year over the next century. Anticipated future supply reductions in British Columbia as a consequence of the pine beetle outbreak vary from 10 to 62% (Patriquin *et al.*, 2007). Forecast substantial declines in suitable habitat for valued tree species in Mexico have been projected (Gómez-Mendoza and Arriaga, 2007; Diaz *et al.*, 2011).

Essential Services: Increased occurrence of drought is projected for southwestern U.S./Northern Mexico, the southern Canadian Prairies and central Mexico, combined with projected increases in water demand due to rapid population growth and agriculture (MacDonald, 2010a; Lal *et al.*, 2011); (Schindler and Donahue 2006). In the Mexico City Metropolitan Area, due to population growth alone, available water per capita is projected to diminish by 11.2% between 2007 and 2030 (Partida and Anzaldo, 2009). Sea-level rise threatens water and electricity infrastructure with inundation and increasing salinity (Sharp, 2010).

26.8.4. Adaptation

26.8.4.1. Evidence of Adaptation

26.8.4.1.1. What are populations doing? Autonomous adaptation

Individuals in North America have been responding to climate change impacts in several ways, for example by purchasing additional insurance, or reinforcing homes to withstand extreme weather (Simmons and Sutter, 2007; Romero-Lankao *et al.*, 2012). When climate change poses significant livelihood impacts, individuals respond by diversifying livelihoods (Newland *et al.*, 2008; Rose and Shaw, 2008) or migrating (Black *et al.*, 2011). Migration can have maladaptive effects at higher levels: many regions experiencing rapid influxes of in-migrants are also among the most vulnerable to climate change impacts (Hugo, 2011).

The propensity to engage in adaptation is strongly influenced by perceived risks of climate change. Residents of the U.S. stand out in international research as holding lower levels of perceived risk of climate change (AXA Ipsos, 2012), which may limit involvement in household-level adaptation.

26.8.4.1.2. What are authorities doing? Planned adaptation

Overall, leadership in adaptation planning is far more evident locally than at other governance levels (Richardson, 2010; Vasseur, 2011; Vrolijks *et al.*, 2011; Carmin *et al.*, 2012a; Henstra, 2012). Many local authorities have not yet moved into the implementation stage, and most of the adaptation programs are in the process of problem diagnosis and adaptation planning (Perkins *et al.*, 2007; Moser and Satterthwaite, 2009; Romero-Lankao and Dodman,

2011).Climate change policies have been motivated by concerns for local economic or energy security and the desire to play leadership roles (Rosenzweig *et al*., 2010; Anguelovski and Carmin, 2011; Romero-Lankao *et al*., 2013). Some of these constitute "integrated" strategies (New York) (Perkins *et al*., 2007; Rosenzweig *et al*., 2010), and in some cases entail coordinated participation of multiple municipalities (Vancouver) (Richardson, 2010). Sector-specific climate risk management plans have also emerged (e.g., water conservation in Phoenix, US and Regina, Canada; wildfire protection in Kamloops, Canada and Boulder, US). Municipalities affected by the mountain pine beetle have taken many steps toward adaptation (Parkins, 2008), and coastal communities in eastern Canada are investing in saltwater marsh restoration to adapt to rising sea levels (Marlin *et al*., 2007). Green roofs, forest thinning and urban agriculture have all been expanding (Chicago, New York, Kamloops, Mexico City), as have flood protection (New Orleans, Chicago), private and governmental insurance policies (section 26.10, Browne and Hoyt, 2000; Ntelekos *et al*., 2010), safe saving schemes (common in Mexico), air pollution controls (Mexico City), and hazard warning systems (Collins and Bolin, 2009; Coffee *et al*., 2010; Romero-Lankao, 2010; Aguilar and Santos, 2011).

Many municipalities are engaged in problem diagnosis and adaptation planning (Perkins *et al*., 2007; Moser and Ekstrom, 2011; Carmin *et al*., 2012b; Romero-Lankao *et al*., 2013). However, few have reached the implementation stage or are comprehensive in scope; and systematic assessments of vulnerability are rare, particularly in relation to population groups (Vrolijks *et al*., 2011). Surveys of municipal leaders showed adaptation is rarely incorporated into planning, due to lack of resources, information and expertise (Horton and Richardson, 2011), and the prevalence of other issues considered higher priority (United States Government Accountability Office, 2009; Romero-Lankao *et al*., 2013), suggesting the need for state- and federal-level facilitation.

26.8.4.2. Opportunities and Constraints

26.8.4.2.1. Adaptation is path-dependent

Adaptation options are influenced by past settlement patterns and decisions. The evolution of cities as economic hubs, for example, affects vulnerability and resilience (Leichenko, 2011). Urban expansion into mountain, agricultural, protected and otherwise risk-prone areas (Boruff *et al*., 2005; McGranahan *et al*., 2007; Collins and Bolin, 2009; Conrad, 2010) invariably alters regional environments. Development histories foreclose some resilience pathways, such as irreversible overexploitation and degradation of water resources (Mexico City) (Romero-Lankao, 2010). Local cultures can pose barriers to adaptation. While strong attachment to place and occupation may motivate willingness to support incremental change, they have been found to serve as barriers to transformational change (Marshall *et al*., 2012). Those same processes, however, may enhance coping capacity and foster learning and adaptation (Collins and Bolin, 2009; Romero-Lankao, 2010; Aguilar and Santos, 2011; Wittrock *et al*., 2011).

26.8.4.2.2. Institutional capacity

Effective adaptation is influenced by access to resources, and the capacity for institutional-level attention and coordination (Burch, 2010; Romero-Lankao *et al*., 2013). Levels of adaptation knowledge and prioritization can be low among some institutional actors, such as municipal planners (Picketts *et al*., 2012), and industries and governmental actors (Spittlehouse, 2008; Brown, 2009). Research has also shed light on the following attributes:

- *Economic Resources:* Rural communities face limited revenues combined with higher costs of supplying adaptation services (Williamson *et al*., 2008; Posey, 2009). Although large cities tend to have greater fiscal capacity, most do not receive financial support for adaptation (Carmin *et al*., 2012b), yet face the risk of higher economic losses.
- *Information and social capital:* Differences in access and use of information, and capacity for learning and innovation, affect adaptive capacity (Romero-Lankao *et al*., 2013). Information access can be limited, even among environmental planners (Picketts *et al*., 2012). The relationship between trust and participation in support networks (social capital) and adaptive capacity is generally positive, however strong social bonds may support narratives that under-estimate risk (Wolf *et al*., 2010; Romero-Lankao *et al*., 2013).

- *Participation:* Long-term effectiveness of adaptation strategies hinges upon the ability to integrate the needs, concerns, and deliberations of all stakeholders, and complementarity with sustainability goals, involving forward-thinking analysis and continuous learning and adjustment (Swanson *et al*., 2010). Considering the overlap among impacts and sources of vulnerability, adaptation planning for human settlements demands an integrative approach. Stakeholder involvement lengthens planning time frames, may elicit conflicts, and power relationships can constrain access (Few *et al*., 2007; Colten *et al*., 2008). But effective stakeholder engagement has tremendously enhanced adaptation planning, eliciting key sources of information regarding social values, and securing legitimacy (Aguilar and Santos, 2011).
- *Multilevel coordination:* Enhancement of vertical inter-governmental coordination for improved resource delivery is key, especially for rural communities (Brklacich *et al*., 2008; Brown, 2009; Sander-Regier *et al*., 2009; Sydneysmith *et al*., 2010). Integrative planning requires horizontal coordination: careful assessment of the layers involved in land-use planning, emergency responses, housing, health and other sectors and their effects on vulnerability at the municipal, neighbourhood and individual levels (Table 26-1). Traditionally, environmental or engineering agencies are responsible for managing climate issues (e.g., Mexico City, Edmonton and London, Canada), but have neither the decision making power nor the resources to address all the dimensions involved. Adaptation planning requires long-term investments by government, business, grassroots organizations and individuals (e.g., Romero-Lankao, 2007; Croci *et al*., 2010; Richardson, 2010; Sarah, 2010).

26.8.4.3. Maladaptation, Trade-Offs, and Co-Benefits

Adaptation strategies may introduce trade-offs or maladaptive effects for policy goals in mitigation, industrial development, energy security, and health (Hamin and Gurran, 2009; Laukkonen *et al*., 2009). Snow-making equipment, for example, mediates snowpack reductions, but is expensive and has high water and energy requirements (Scott *et al*., 2007). Irrigation and air conditioning have immediate adaptive effects, but are energy-consumptive. Sea walls protect coastal properties, yet negatively affect the structure and functioning of coastal ecosystems (Richardson, 2010).

Conventional sectoral approaches to risk management and adaptation planning undertaken at different temporal and spatial scales have exacerbated vulnerability in some cases (Eakin *et al*., 2010; Romero-Lankao, 2012)(Doves 2009). Approaches that delegate response planning to residents in the absence of effective knowledge exchange have resulted in maladaptive effects (Friesinger and Bernatchez, 2010).

Other strategies offer potential synergies and co-benefits. Policies addressing air pollution (Harlan and Ruddell, 2011) or housing for the poor (Colten *et al*., 2008) can often be adapted at low or no cost to fulfill adaptation and sustainability goals simultaneously (Badjek *et al*., 2010). Efforts to temper declines in production or competitiveness in rural communities could involve mitigation innovations, including carbon sequestration forest plantations (Holmes, 2010). Painting roofs white reduces the effects of heat and lowers energy demand for cooling (Akbari *et al*., 2009).

Adaptation planning can be greatly enhanced by incorporating region-specific vulnerability information, so socio-economic vulnerabilities can be targeted (Clark *et al*., 1998). Methods for mapping environmental and socio-economic vulnerability have been improved and widely utilized (Romero-Lankao *et al*., 2013). Similarly, strategies supporting cultural preservation and subsistence livelihood needs among indigenous peoples would enhance effectiveness (Ford *et al*., 2010), as would integrating traditional culture with other forms of knowledge, education and economic development (Hardess *et al*., 2011).

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Box 26-3. Responding to Climate Change in Three North American Cities

With growing populations of 20.5, 14 and 2.3 million people, respectively, the metropolitan areas of Mexico City, New York and Vancouver are facing multiple risks climate change is predicted to aggravate. These risks range from

sea level rise, coastal flooding and storm surges in New York and Vancouver to heat waves, heavy rains and associated flooding, air pollution, and heat-island effects in all the three cities (Leon and Neri, 2010; Magana, 2010; Rosenzweig and Solecki, 2010; City of Vancouver, 2012). Many of these risks result not only from long-term global and regional processes of environmental change, but also from local changes in land and water uses and in atmospheric emissions induced by urbanization (Magana, 2010; Romero-Lankao, 2010; Kinney *et al*., 2011; Solecki, 2012).

Despite the compound risks they are facing, the three cities have shown promise as innovators of climate relevant actions as they have moved to institutionalize their climate agendas. In Mexico City, the Program of Climate Action 2008–2012 (PAC) and the 2011 Law for Mitigation and Adaptation to Climate Change are parts of a larger 15-year "Green Agenda", which focuses mainly on reducing 7 million tonnes of CO2 equivalent between 2008-2012 through mitigation actions, with these efforts accounting for 94.3% of its total budget expenditures between 2008 and 2012 (Romero-Lankao *et al*., 2012). Similarly, in 2005 New York City's Plan to reduce GHG by 30% from 2005 levels is mitigation centered, as is Vancouver' 2007 Greenest City Plan calling for a 33% reduction in GHG emissions below 2007 levels by 2020. However, mitigation became in 2007 part of New-York's long-term sustainability plan that included adaptation concerns with climate actions intended to protect city's infrastructures and buildings (Solecki, 2012; Ray *et al*., 2013), while Vancouver launched the first comprehensive municipal adaptation plan in Canada in July 2012. The shifts in focus from mitigation to adaptation have followed as it has become increasingly clear that even if mitigation efforts are wholly successful, some adverse impacts due to climate change are probably unavoidable.

City mayors and other urban actors have often played key roles in launching climate policies. Mayor Michael Bloomberg of New York and Mayor Marcello Ebrard of Mexico City have, respectively, chaired the C40 and World Mayors Council on Climate Change. Scientists, private sector actors and nongovernmental organizations have been of no lesser importance. To take advantage of a broad based interaction between various climate change actors, Mexico City has set up a Virtual Climate Change Center, a boundary organization intended to serve as a repository of knowledge, models and data on climate change impacts, vulnerability and risks (Romero-Lankao *et al*., 2012). Information sharing by climate change actors has also taken place in New York, where scientists, and insurance and risk management experts have served on the Panel on Climate Change to advise the city on the science of climate change impacts and "protection levels specific to the city's critical infrastructure" (Solecki, 2012): 564).

Notwithstanding these positive pressures, however, climate policies in the three cities are faced with many challenges. Inconsistencies among the three tiers of government approaches (or lack thereof) to climate change are a barrier to effective responses in Vancouver (Burch, 2010). Fragmented governance structures in Mexico City and New York prevent these cities from having jurisdictional control over how their three regionally interdependent states (i.e., Federal District, Mexico and Hidalgo for Mexico City and Connecticut, New Jersey and New York for New York) respond to climate change (Romero-Lankao *et al*., 2012; Solecki, 2012). There are also conflicts in priorities and objectives between various actors and sectors moving city policy. For instance, authorities in Mexico City are concerned with avoiding growth into risk-prone areas and into conservation areas providing ecosystems-services (Aguilar and Santos, 2011). However, these priorities compete for regulatory space within a policy agenda that is already coping with a very wide range of economic and developmental imperatives (Romero-Lankao *et al*., 2012). Cultural barriers across stakeholders in the Vancouver region, lack of leadership and of strategies facilitating the effective use of existing resources are notable constraints to effective adaptation (Burch, 2010).

The climate plans of the three cities are far reaching and include mitigation and adaptation strategies that are related to their sustainable development goals. However, few of the proposed actions will result in immediate effects, and instead call for additional planning. This highlights the significant effort that is necessary for comprehensive responses. There are also differences in what the three cities emphasize in their climate action plans. For instance, the three cities differ in their levels of emphasis on infrastructural protection. Mexico City seeks to reduce water and transportation emissions through such actions as improvements in infrastructure and changes in transportation mode-share. Vancouver has prioritized the separation of sanitary and stormwater, yet this adaptation is not expected to be complete until 2050 (City of Vancouver, 2012). It will also take New York much time, money and energy to expand adaptation strategies beyond the protection of water supply, sewer, and wastewater treatment systems to include all essential city infrastructures (Ray *et al*., 2013);

Climate responses require new types of scientific information at very local scales, e.g., vulnerability analyses, flood risk assessments, health impacts analyses, and these are not always available (Romero-Lankao *et al*., 2012; Ray *et al*., 2013). Little is known, for instance, about how to predict and respond to common and differential levels of risk experienced by different populations within cities. Although some scholarship exists on disparities in household or population level vulnerability and adaptive capacity (Cutter *et al*., 2003; Villeneuve and Burnett, 2003; Douglas *et al*., 2012; Romero-Lankao *et al*., 2013), equity concerns in all three cities have gotten little attention as the cities have focused on reducing emissions (Mexico City), or protecting critical infrastructures (New York and Vancouver). Yet, even when local needs are identified, such as the need to protect higher risk homeless and low-income populations, they are often not addressed in action plans, as risk planning and long term adaptation strategies give way to shorter term priorities and economic imperatives.

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26.9. Federal and State Level Adaptation

Besides adaptations at the city level (section 25.7), governments at the federal, state/provincial, and local levels across North America are developing climate change adaptation plans. These initiatives, which began at the provincial (e.g., Nunavut (Nunavut Department of Sustainable Development, 2003)) and municipal (e.g., Keene, New Hampshire (City of Keene, New Hampshire and ICLEI - Local Governments for Sustainability, 2007)) levels, appear to be preliminary and relatively little has been done to implement specific measures.

26.9.1. Federal Level

All three national governments are addressing adaptation to some extent, with a national strategy and a policy framework (Mexico), a federal policy framework (Canada), and the United States having all federal agencies develop adaptation plans.

In 2005, the Mexican government created the *Inter-Secretarial Commission to Climate Change* (CICC – Comisión Inter-Secretarial de Cambio Climático) to coordinate national public policy on climate change (Comisión Inter-Secretarial de Cambio Climático, 2005; SEMARNAT, 2010; Sosa-Rodriguez, 2013).The government's initiatives are being delivered through the *National Strategy for Climate Change 2007-2012* (Intersecretarial Commission on Climate Change, 2007) and, the *Special Programme on Climate Change 2009-2012*, which identify priorities in research, cross-sectoral action such as developing early warning systems, and capacity development to support mitigation and adaptation actions (Comisión Inter-Secretarial de Cambio Climático, 2009). The *Policy Framework for Medium Term Adaptation* (Consejo Intersecretarial de Cambio Climático, 2010)aims at framing a single national public policy approach on adaptation with a time-horizon up to 2030. The General Law of Climate Change requires state governments to implement mitigation and adaptation actions (Diario Oficial de la Federación, 2012).

Canada is working towards creating a Federal Adaptation Policy Framework intended to mainstream climate risks and impacts into programs and activities to help frame government priorities (Government of Canada, 2011). In 2007, the federal Government made a four-year adaptation commitment to develop six Regional Adaptation Collaboratives (RAC) in provinces across Canada, ranging in size and scope, from flood protection and drought planning, to extreme weather risk management; and assessing the vulnerability of Nunavut's mining sector to climate change (Natural Resources Canada, 2011). In 2011, the federal government renewed financial support for Environment Canada's Climate Change Prediction and Scenarios Program and Canada's Heat Alert and Response System, and provided new funding to create a Climate Adaptation and Resilience Program for Aboriginals and Northerners, and to finance the integration of adaptation into National Codes and Standards (Environment Canada, 2011).

The U.S. government embarked in 2009 on a federal government wide effort to have all federal agencies address adaptation; to apply understanding of climate change to agency missions and operations; to develop, prioritize, and

implement actions; and to evaluate adaptations and learn from experience (The White House, 2009; Bierbaum *et al.*, 2012). The U.S. Government provides technical and information support for adaptation by non-federal actors, but does not provide direct financial support for adaptation (Parris *et al.*, 2010).

Some federal agencies took steps to address climate change adaptation prior to this broader interagency effort. In 2010, the U.S. Department of Interior created Climate Science Centers to integrate climate change information and management strategies in eight regions and 21 Landscape Conservation Cooperatives (Secretary of the Interior, 2010), while the U.S. Environmental Protection Agency's Office of Water developed a climate change strategy (U.S. Environmental Protection Agency National Water Program, 2011).

26.9.2. State and Provincial Levels

A number of states and provinces in all three countries have developed adaptation plans. For example, Ontario's 2011-2014 adaptation strategy and action plan identifies 37 measures, including requiring that building codes be revised to increase resilience and increase water and energy conservation (Government of Ontario, 2011). Quebec updated their plan which covers a number of managed sectors and ecosystems (Government of Quebec, 2012). British Columbia is modernizing its *Water Act* to alter water allocation during drought to reduce agricultural crop, livestock loss and community conflict, while protecting aquatic ecosystems (British Columbia Ministry of the Environment, 2010).

In the U.S. California was the first state to publish an adaptation plan calling for a 20% reduction in per capita water use by 2020 (California Natural Resources Agency, 2009). Maryland first developed a plan on coastal resources and then broadened it to cover human health, agriculture, ecosystems, water resources, and infrastructure (Maryland Commission on Climate Change Adaptation and Response Working Group, 2008; Maryland Department of the Environment on behalf of the Maryland Commission on Climate Change, 2010). The State of Washington is addressing environment, infrastructure, and communities; human health and security; ecosystems, species, and habitat; and natural resources (Washington State Built Environment: Infrastructure & Communities Topic Advisory Group (TAG), 2011; Washington State TAG 4 Natural Resources Working Lands and Waters, 2011; Washington State Topic Advisory Group (TAG) Report- TAG 2 Human Health and Security, 2011; Washington State Topic Advisory Group 3 Species, Habitats and Ecosystems, 2011).

In Mexico, Veracruz, Mexico City, Nuevo León, Guanajuato, Puebla, Tabasco, and Chiapas, have all developed their *State Programmes for Climate Change Action* (Programas Estatales de Acción ante el Cambio Climático - PEACC), while Baja California Sur, Hidalgo, and Campeche are in the final stage and 17 states are still in the planning and developing stage (Instituto de Ecología del Estado de Guanajuato, 2011). The proposed adaptation actions focus mainly on: 1) reducing physical and social vulnerability of key sectors and populations; 2) conservation and sustainable management of ecosystems, biodiversity, and ecosystem services; 3) developing risk management strategies; 4) strengthening water management; 5) protecting human health, and; 6) improving current urban development strategies, focusing on settlements and services, transport and land use planning.

26.9.3. Barriers to Adaptation

Of the three national governments, only Mexico requires that states develop adaptation plans. Most adaptation activities have only involved planning for climate change and few measures have been implemented (Preston *et al.*, 2010; Bierbaum *et al.*, 2012).

Even though Canada and the U.S. are relatively well-endowed in their capacity to adapt, there are significant constraints on adaptation (Chapter 16), with financing being a significant constraint in all three countries(Carmin *et al.*, 2012a). Barriers include legal constraints (e.g., Jantarasami *et al.*, 2010) lack of coordination across different jurisdictions (Smith *et al.*, 2009; National Research Council, 2010; INECC-SEMARNAT, 2012), leadership (Smith *et al.*, 2009; Moser and Ekstrom, 2010), and divergent perceptions about climate change (Bierbaum *et al.*, 2012). Although obtaining accurate scientific data was ranked less important by (Carmin *et al.*, 2012a), an important

constraint is lack of access to scientific information and capacity to manage and use it (Moser and Ekstrom, 2010; INECC-SEMARNAT, 2012). Adaptation activities in the U.S. tend to address hazards and propose adaptations that tend to protect current activities rather than facilitate long term change. In addition, the adaptation plans generally do not attempt to increase adaptive capacity (Eakin and Patt, 2011).

26.10. Key Multi-Sectoral Risks, Uncertainties, Knowledge Gaps, and Research Needs

26.10.1. Key Multi-Sectoral Risks

We close this chapter with our assessment of key current and future regional risks (Figure 26-6). These figures illustrate how *relative* risks within a sector can change based on increases in the magnitude and rate of climate change and adaptation levels. However, the assignment of *absolute* risk by sector/system and relative risk across sectors/systems and regions should be interpreted with much caution for different reasons. Risks in *terrestrial ecosystems* and *coastal systems* lend themselves better to *predictions* based on models that mix historical and theoretical information. That is not the case with the complexity of key risks in such systems and sectors as water resources and management, food security, and urban and rural settlements, where differences in the severity of climate risks are likely to be strongly influenced by context-specific societal and environmental factors and processes (e.g., population and economic growth, governance, land use change, etc.) whose future trajectories are inherently unpredictable, or unknown. That can be the reason why it was harder for team authors to assign risk levels in the areas of human security, livelihoods and poverty.

[INSERT FIGURE 26-6 HERE
Figure 26-6: Estimated climate risk to key sectors and systems in North America, for different time frames (2030-2040 and 2080-2100), under two levels of global warming (2°C and 4°C), and diverse assumptions about anticipated adaptation. Levels of risk and levels of anticipated adaptation are differentiated by colored shading and ranges from low to high. They represent the judgment of North American individual authors who have different approaches or "ways of knowing" and assessing risks, and realize that generalizations over an area as heterogeneous as North America can be difficult to interpret.]

This figure assigns a single score to sectors and systems that contain a wide array of risks amongst their components. Consider for example agriculture. Although projected changes in temperature, precipitation and extreme events are predicted to result in notable productivity declines in major North American crops, vulnerability to climate varies considerably depending on the extent to which farmers and communities have access to financial resources, technology, institutional support mechanisms and social networks. Risk in rural and urban settlements and economy sectors can vary considerably depending on context-specific social and physical factors faced by different communities, individuals, and firms. Even in biophysical coastal and terrestrial ecosystems, vulnerability varies widely across individual species and landscapes. Furthermore, the rate of change matters in ecosystems (e.g., 2C by 2040 is more risky than 2C by 2080). In short the judgments on risk in this figure are intended to apply to each sector as a whole, but should *not* be interpreted to mean that all components of the sector face the same level of risk.

A further key consideration is that the judgments about risk conveyed by these figures were made by experts living under current socio-economic conditions, not being able as such to fully anticipate potential future changes. Yet over the course of the 21st century, socioeconomic conditions will very likely change considerably for many sectors, systems and places. The dynamics of wealth generation and distribution, technological innovations, institutions, even culture, can substantially affect what level of risk can be absorbed by the North American systems and sectors considered in Figure 26-6. Under the conditions and estimations of risk depicted in the figure it is, hence, highly likely that in the near term (*the era of climate responsibility*), risks associated with committed climate changes can be managed primarily through adaptation actions. However, current mitigation actions can help reduce risks during the second half of the century (*the era of climate options*).

26.10.2. Uncertainties, Knowledge Gaps, and Research Needs

The literature on climate impacts, adaptation and vulnerability in North America has grown considerably, as has the diversity of sectors and topics covered (e.g., urban and rural settlements, food security, and adaptation at local, state and national levels). However, limitations in the topical and geographical scope of this literature are still a challenge (e.g., more studies have focused on insurance than on economic sectors such as industries, construction and transportation). It is also challenging to summarize results across many studies and identify trends in the literature when there are differences in methodology, theoretical frameworks and causation narratives (e.g., between outcome and contextual approaches) making it hard to compare "apples to oranges" (Romero-Lankao *et al.*, 2012) While the US and Canada have produced large volumes of literature, Mexico lags well behind. It was, therefore, difficult to devote equal space to observed and projected impacts, vulnerabilities and adaptations in Mexico in comparison with its Northern neighbors. With its large land area, population and important, albeit understudied, climate change risks and vulnerabilities, more climate change research focusing on Mexico is direly needed.

The literature on North America tends to be dominated by sector level analyses. Yet, climate change interacts with other physical and social processes to create differential risk and impact levels. These differences are mediated by context-specific physical and social factors shaping the vulnerability of exposed systems and sectors. Furthermore, while studies often focus on isolated sectorial effects, impacts happen in communities, socio-ecologic systems and regions, and shocks and dislocations in one sector or region often affect other sectors and regions due to social and physical interdependencies. This point is illustrated by our border region and wildfire boxes and the human settlements section, which discuss place-based impacts, vulnerabilities and adaptations. Unfortunately, literature using placed-based or integrated approaches to these complexities is limited. Indeed although in early drafts the authors of this chapter attempted to put more emphasis on place-based analysis and comparisons, the literature was inadequate to support such an effort. The IPCC includes chapters on continents and large regions to make it possible to assess how multiple climate change impacts can affect these large areas. However, this macro view gives insufficient detail on context specific local impacts and risks, missing the on-the-ground reality that the effects of climate change are and will be experienced at much smaller scales, and those smaller scales are often where meaningful mitigation and adaptation actions can be generated. In order to give local actors relevant information on which to base these local actions, more research is needed to better understand the local and regional effects of climate change across sectors.

Frequently Asked Questions

FAQ 26.1: What makes North America especially unique compared with other continents when it comes to climate vulnerabilities?

North America is unique in the very broad diversity of geography, climate, economic development, social fabric and governance systems which can be found across its broad landmass, and result in different vulnerabilities and capacities to adapt across sectors and regions. Layered on top of this broad diversity is a similarly broad range of climate trends and projections. For example rapid observed and projected further warming of northern NA will lead to major changes in transportation, agriculture, and native livelihoods. Meanwhile, strong drying trends in the western US and Mexico are leading to major stresses on water supplies, agriculture, and ecological services.

FAQ 26.2: Will changing patterns of precipitation be experienced in NA and if so, in what ways?

Future projections over NA suggest increases in annual precipitation in Canada and Alaska. However decreases in the southwestern US and much of Mexico are projected. These average trends will be accompanied by increasing intensity of precipitation events along with longer, more intense periods of draught. Thus, variability in precipitation appears to be a hallmark of future climate in NA. Extreme storm events can have significant impacts on local infrastructure and human health when they exceed the intensity for which these systems have been developed over many decades. The large concentration of human and infrastructure resources in the Gulf of Mexico and other coastal regions can exacerbate this vulnerability.

FAQ 26.3: What sectors/regions are more vulnerable? What factors/drivers contribute to a vulnerable situation?

- *Water supplies and quality in many regions*: Runoff throughout most of Mexico, except the south, much of the western United States and southwestern Canada is likely to decrease. These areas are already facing stress from limited water supply and lower future runoff is likely to result in increased competition for water supplies, decreased agricultural production, and harm to aquatic ecosystem.
- *Agriculture in Mexico*, particularly among smallholders: Higher temperatures, a decrease in runoff, and lower soil moisture, which are all considered to be likely for many agricultural-producing areas of Mexico, will likely decrease agricultural production. Only a small proportion of cultivated land is irrigated, furthermore, and the availability of insurance to small-holders in particular is limited. This risks reducing food security, and increasing social instability and migration. Mention something about the wet tropical south
- *Many ecosystems*: In particular, wildfire and pest outbreaks have increased in North America and both of these trends have been linked to climate change. Forest ecosystems, forest-based industries, and human settlements have been impacted negatively by recent wildfire and pest events. Forecasts indicating increasing frequency and intensity of both processes suggest a high likelihood for further reductions in biodiversity, loss of habitat, decreases in ecosystem services, challenges for forest-based industries, and increased economic and health consequences for local communities

FAQ 26.4: What lessons can be drawn from existing adaptation actions on the factors shaping effective responses?

Different economic and demographic sectors and tiers of government are starting to assess their climate change vulnerabilities and designing adaptation programs. Many responses are in diagnosis and planning stage and have not yet moved into the implementation.

Engaging stakeholders in adaptation has proved effective in gaining legitimacy for public decisions and helping capture local realities. The use of scientific information in participatory exercises has also been crucial. However, potential issues might arise: delays in decision making; tensions and conflicts among stakeholder groups embedded in power relationships that can constrain the access of the general population to decision making processes. In addition, adaptation may be constrained by a general unwillingness to address long-term changes (e.g., many decision makers have relatively short term planning and management horizons).

Adapting to climate change is complicated by the fact that it is undertaken at different temporal, spatial and sectoral scales, thus requiring a careful assessment of the different sectoral and spatial layers involved (e.g., land-use planning, emergency responses, housing, and health). Often, environmental or engineering agencies are responsible for managing climate issues, but do not have the decision making power nor the resources available to address all the dimensions involved. Adaptation requires not only shorter term actions, but also longer term measures and perspectives by the different tiers of governmental, businesses, grassroots organizations and individuals.

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Table 26-1: Dimensions of vulnerability. Source: Romero-Lanka, 2012.

Climate Hazards	**System/Sector of concern**	**Impacts (changes in)**	**Determinants of adaptive capacity/resilience**	
			City wide	***Individual level***
Sea level rise	Health	Disease	Land use planning	Age
Temperature	Energy	Mortality	Urban design	Gender
Precipitation	Built environment	Water availability	Infrastructures	Ethnicity
Heat waves	Economic sector	Air & water quality	Services (water, waste)	Migration status
Storm-surge	Demographic group	Economic disruptions	Housing	Income
	Infrastructure	Migration	Social capital	Education
	Transport	Financial losses	Economic base	Health conditions
	Hinterland	Livelihoods	Policy (emergency) response	Knowledge, experience
	Ecosystem services		Governance	Savings
				Insurance
				Risk perceptions

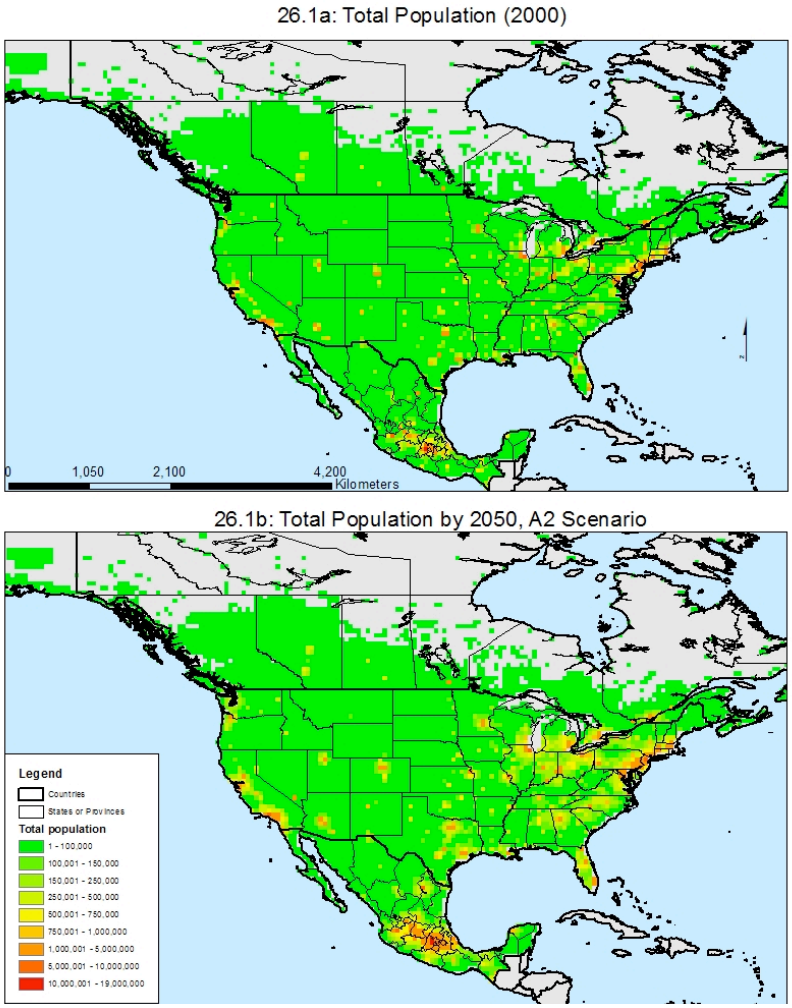

Figure 26-1: Current and future populations in North America. While concentrations of growing populations, infrastructures, and sectors in urban areas can be a source of risk, geographic isolation of rural populations can be a source of sensitivity that is aggravated by high dispersion levels. Source: Lutz, 2007.

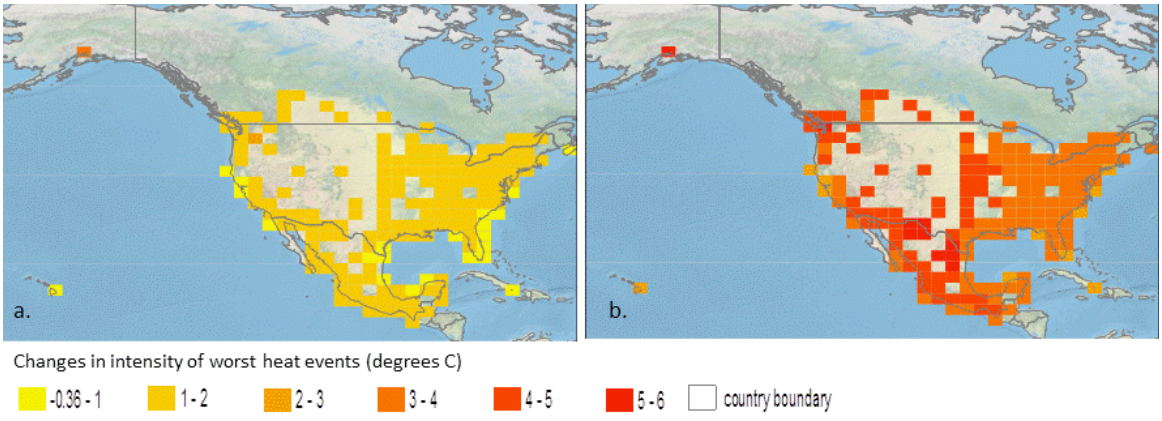

Figure 26-2: Projected changes in the intensity of the worst heat events, as simulated by CLMU for urban grid cells: a) near term (2020-2039) relative to present-day climate (1980-1999); b) end of the 21st century (2080-2099) relative to present-day climate (1980-1999). Source Wilhelmi et al. (forthcoming).

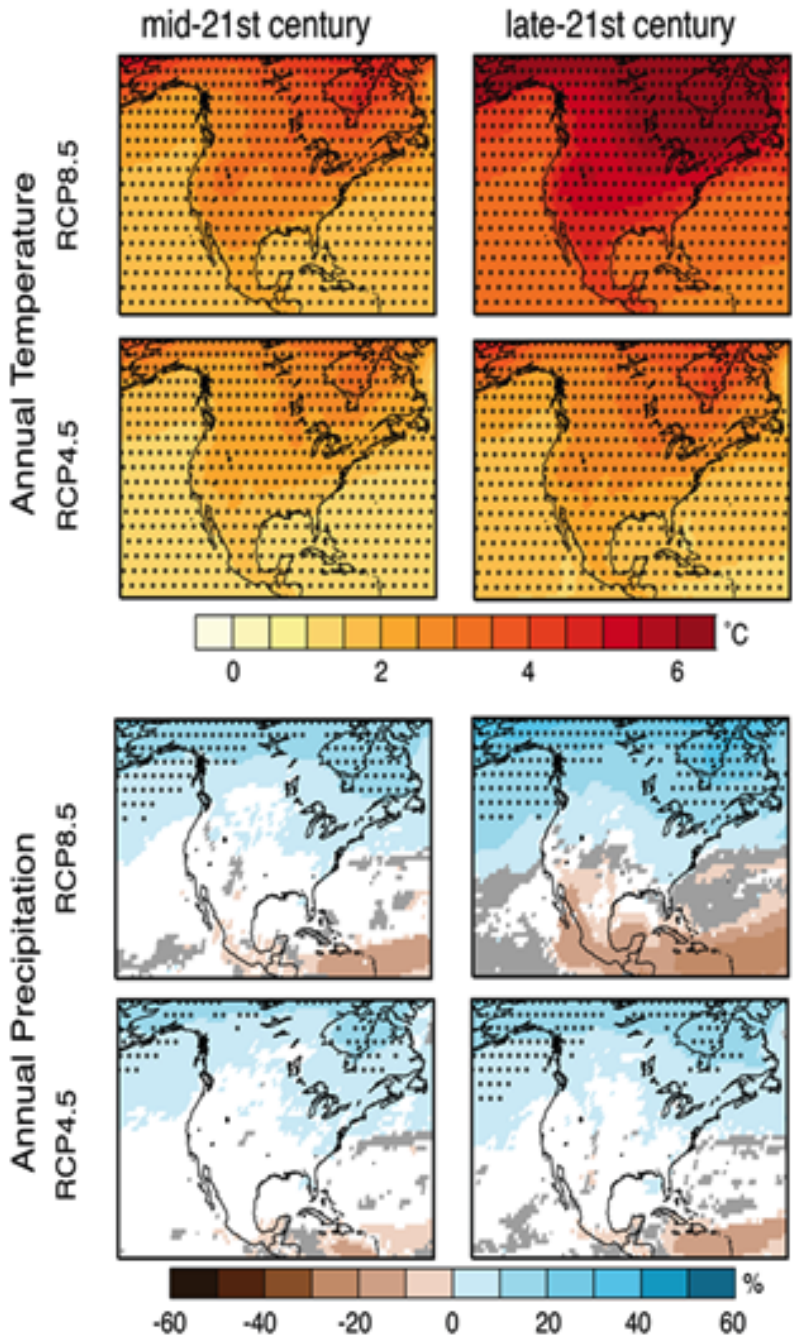

Figure 26-3: Changes in annual temperature and precipitation. White indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st century period is 2081-2100. The mid-21st century period is 2046-2065.

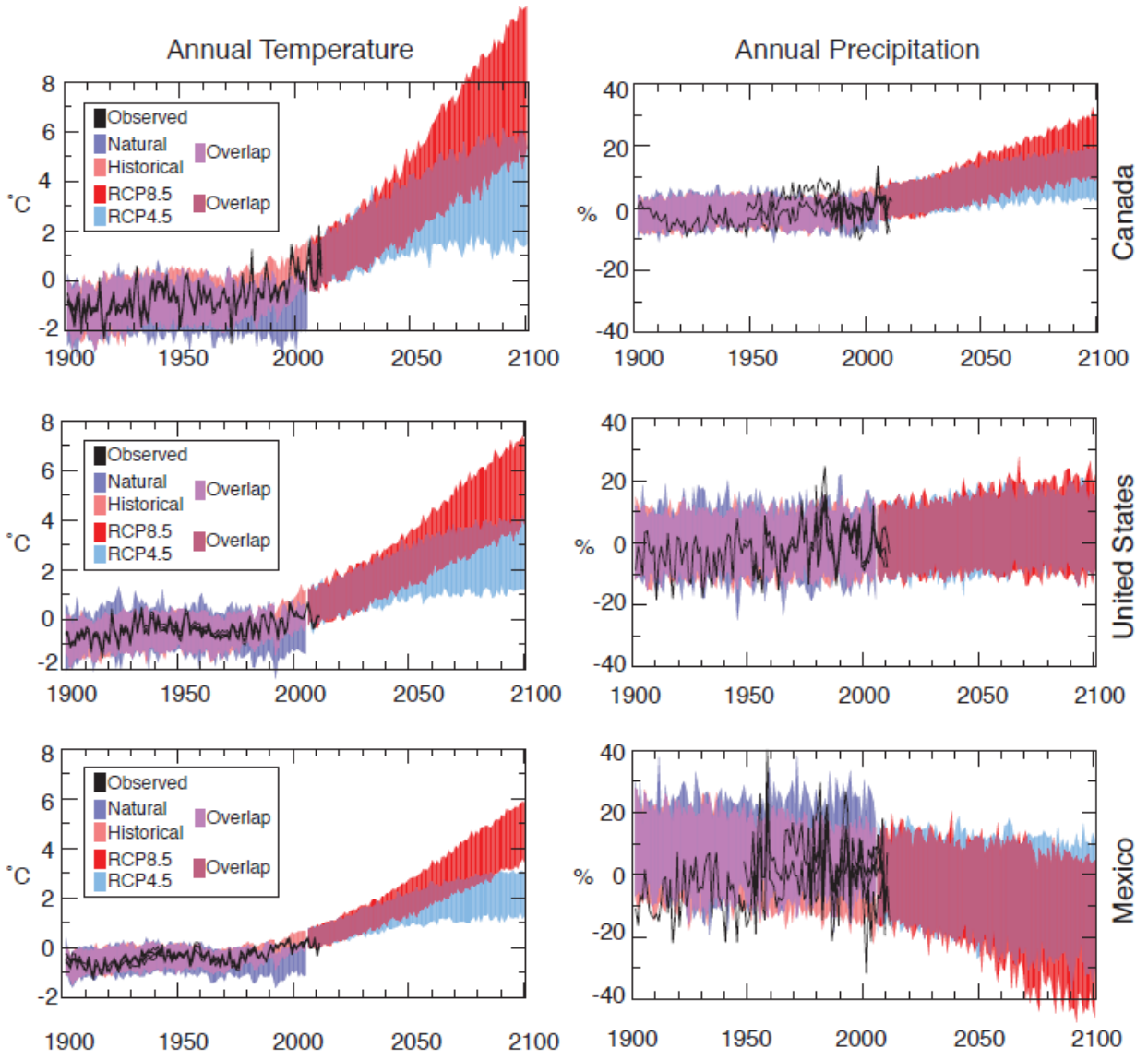

Figure 26-4: Observed and simulated variations in past and projected future annual average precipitation and temperature over land areas of Canada, the contiguous United States, and Mexico. Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.

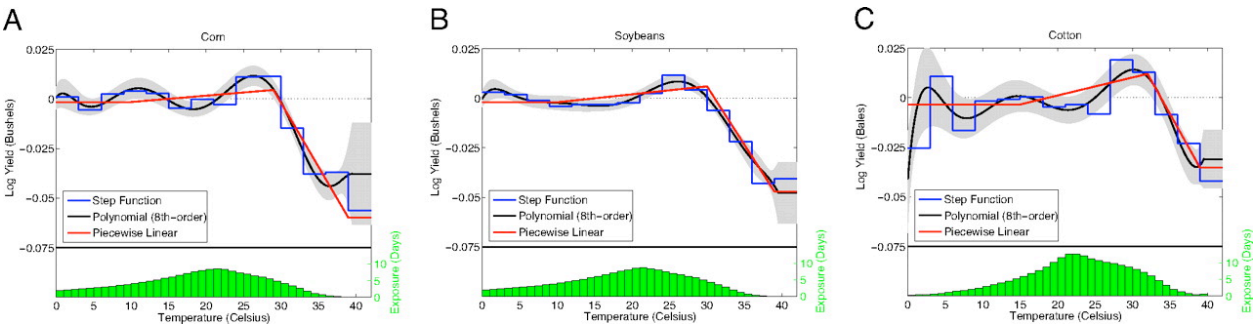

Figure 26-5 Nonlinear relation between temperature and yields. Source: Schlenker, 2009.

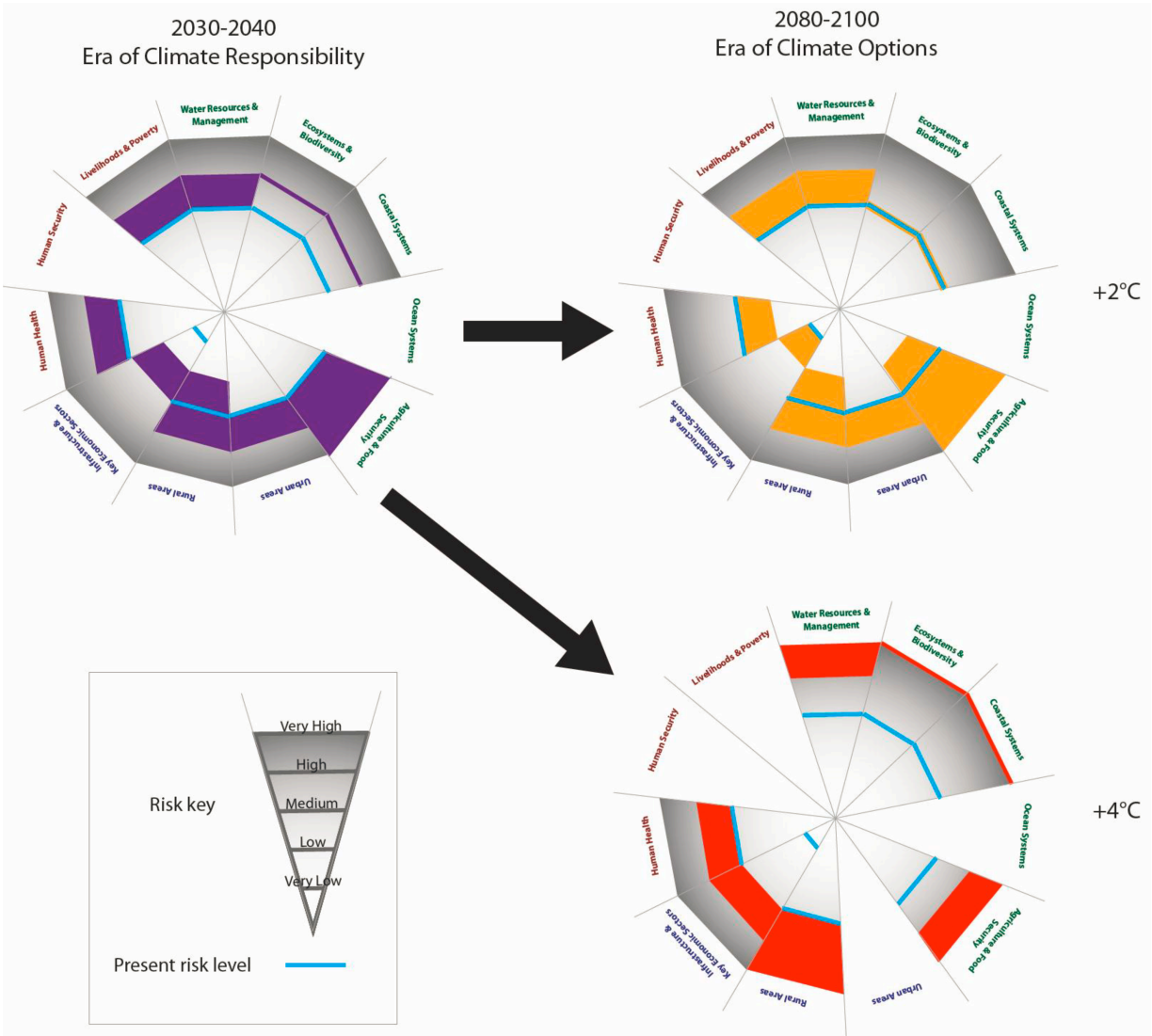

Figure 26-6: Estimated climate risk to key sectors and systems in North America, for different time frames (2030-2040 and 2080-2100), under two levels of global warming (2°C and 4°C), and diverse assumptions about anticipated adaptation. Levels of risk and levels of anticipated adaptation are differentiated by colored shading and ranges from low to high. They represent the judgment of North American individual authors who have different approaches or "ways of knowing" and assessing risks, and realize that generalizations over an area as heterogeneous as North America can be difficult to interpret.

Chapter 27. Central and South America

Coordinating Lead Authors
Graciela Magrin (Argentina), José Marengo (Brazil)

Lead Authors
Jean-Phillipe Boulanger (France), Marcos Buckeridge (Brazil), Edwin Castellanos (Guatemala), Germán Poveda (Colombia), Fabio R. Scarano (Brazil), Sebastián Vicuña (Chile)

Contributing Authors
Erik Alfaro (Costa Rica), Fabien Anthelme (France), Jonathan Barton (UK), Nina Becker (Germany), Arnaud Bertrand (France), Ulisses Confalonieri (Brazil), Carlos Demiguel (Spain), Bernard Francou (France), Rene Garreaud (Chile), Iñigo Losada (Spain), Melanie McField (USA), Carlos Nobre (Brazil), Patricia Romero Lankao (Mexico), Paulo Saldiva (Brazil), Jose Luis Samaniego (Mexico), Amanda Pereira de Souza (Brazil), María Travasso (Argentina), Ernesto Viglizzo (Argentina), Alicia Villamizar (Venezuela)

Review Editors
Leonidas Osvaldo Girardin (Argentina), Jean Ometto (Brazil)

Volunteer Chapter Scientist
Nina Becker (Germany)

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Frequently Asked Questions
27.1: What is the impact of receding glaciers on natural and human systems in the tropical Andes?
27.2: Can PES be used as an effective way for helping local communities to adapt to climate change?
27.3: Are there emerging and re emerging human diseases as a consequence of climate variability and change in the region?

References

Executive Summary

Changes in climate variability and in extreme events have been severely affecting Central America (CA) and South America (SA) during the last 60 years. Increases in observed warm days and decreases in cold days and nights have been identified in CA, Northern SA, Northeast Brazil (NEB), Southeastern South America (SESA) and the West Coast of SA (medium-lower confidence). More frequent and intense rainfall extremes in SESA have favored an increase in the occurrence of landslides and flash floods (low confidence). On seasonal scales, it is likely that changes in hydrometeorological extremes in regions such as Amazonia, La Plata basin and Northern South America observed during the last 10 years have been related to changes in natural climate variability, determining changes in extreme streamflow variability in the La Plata and Amazon Rivers (27.1.2.2, 27.2.1.1).

The projected mean warming for CA by the end of the century, according to different global and regional climate models from the CMIP3 and CMIP5 ranges from 1.5°C to 4.0 °C, while rainfall tends to decrease between 5 and 10% by 2100. SA shows a warming between 1.0°C to 5.0 °C, with rainfall reduction up to 10% in tropical SA and an increase of about 10-15% in SESA. Projections for the 21st century from CMIP3 global models suggest a weakening of the North American Monsoon System NAMS and precipitation reduction in June-July, accompanied by projected warming in most of CA (medium confidence). Analyses from global and regional models in SA show common patterns of projected climate in some sectors of the continent, with a very likely increase of precipitation in SESA, Northwest of Peru and Ecuador and western Amazonia, while decreases are projected for northern SA,

Eastern Amazonia, central eastern Brazil, NEB, the Altiplano and southern Chile. With lower-medium confidence, heavy precipitation is likely projected to increase in SESA, while dry spells would increase in northeastern South America. Increases in warm days and nights are very likely to occur in most of SA (27.2.1.2).

In CA and SA there is evidence of changing conditions in terms of geophysical variables (cryosphere and runoff) that affect streamflow and finally water availability (high confidence). Since AR4, there is growing evidence that glaciers (both tropical and extratropical) are retreating and the cryosphere in the Andes is changing according to the warming trends. These changes affect streamflow availability in different seasons of the year. Robust trends are apparent associated with changes in precipitation such as increasing runoff in the SESA region (La Plata basin), and reducing runoff in the Central Andes (Chile, Argentina) and Central America. In contrast to these findings, no robust trend in streamflow in the Amazon Basin has been detected (27.3.1.1).

Land cover change is a key driver of environmental change with significant impacts that may increase the potential negative impacts from climate change. Deforestation and land degradation are mainly attributed to increased extensive and intensive agriculture, both from traditional export activities such as beef and soy production, but more recently from biomass for biofuel production. The agricultural expansion has affected fragile ecosystems such as the edges of the Amazon forest and the tropical Andes increasing the vulnerability of communities to extreme climate events, particularly floods, landslides and droughts. Even though deforestation rates in the Amazon have decreased substantially in the last eight years to a current value of 0.29%, the lowest for all forest biomes in Brazil, other regions like the Cerrado and the Chaco forests still present high levels of deforestation with rates as high as 1.33% (27.2.2.1).

Socioeconomic development shows a high level of structural heterogeneity and a very unequal income distribution resulting in high vulnerability of the region to climate change. There is still a high and persistent level of poverty in most countries of the region (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade. In terms of human development, the performance of different countries varied greatly from Chile and Argentina at the high end of human development, and Guatemala and Nicaragua with the lowest indices. The economic inequality translates into inequality in access to water, sanitation and adequate housing, particularly for the most vulnerable groups: indigenous peoples, Afro-descendants and women living in poverty which translates into low adaptive capacities to climate change for these groups (27.2.2.2).

Coastal and marine ecosystems have been undergoing significant transformations that pose threats to fish stocks, corals, mangroves, places for recreation and tourism, and controls of pests and pathogens. Frequent coral bleaching events have been recently reported for the Mesoamerican Coral Reef. In CA and SA, some of the main drivers of mangrove loss are deforestation and land conversion, agriculture and shrimp ponds to an extent that the mangroves of the Atlantic and Pacific coasts of CA are some of the most endangered in the planet. Changes over 2 mm/yr of sea-level rise (SLR) have been found in CA and SA, which is reason for concern since 3/4 of the population of the region live within the range of 200 km of the coast (27.3.3.1). In Brazil, fisheries' co-management - a participatory process involving local fishermen communities, government, academia and NGOs - favors a balance between conservation of marine fisheries, coral reefs and mangroves, and the improvement of livelihoods, as well as the cultural survival of traditional populations (27.3.3.2).

Conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss in the region, and in parallel is a driver of anthropogenic climate change. Plant species are rapidly declining in CA and SA; the highest percentage of rapidly declining amphibian species occurs also in CA and SA; with Brazil being among the countries with most threatened bird, mammal species and freshwater fish. However, the region has still large extensions of natural vegetation cover for which the Amazon is the main example. Ecosystem-based Adaptation practices, such as conservation agreements and community management of natural areas, begin to multiply across the region (27.3.2.2).

Although there is high uncertainty in terms of climate change projections for regions with high vulnerability in terms of current water availability, this vulnerability is expected to increase in the future due to climate change impacts (high confidence). Already vulnerable regions in terms of water supply, like the semi-arid zones in Chile-Argentina, North Eastern Brazil and Central America and the tropical Andes, are expected to increase even further their

vulnerability due to climate change. Glacier retreat is expected to continue, and a reduction in water availability due to expected precipitation reduction and increase evapotranspiration demands is expected in the semi-arid regions of CA and SA. These scenarios would affect water supply for large cities, small communities, hydropower generation and the agriculture sector (27.3.1.1, 27.3.1.2, 27.6.1). Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability. Constitutional and legal reforms towards more efficient and effective water resources management and coordination among relevant actors in many countries in the region (e.g. Honduras, Nicaragua, Ecuador, Peru, Uruguay, Bolivia and Mexico) also represent an adaptation strategy to climate variability and change (27.3.1.2).

Changes in agricultural productivity attributed to climate change are expected to have a great spatial variability**.** In SESA, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (SRES: A2, B2) (medium confidence). In CA, northeast of Brazil and parts of the Andean region increases in temperature and decreases in rainfall could decrease the productivity in the short-term (before 2025), threatening the food security of the poorest population (medium confidence). The great challenge for CA and SA will be to increase the food and bioenergy production and at the same time to sustain the environmental quality in a scenario of climate change (27.3.4.1).

Renewable energy (RE) has a potential impact on land use change and deforestation, but at the same time will be an important means of adaptation, with the region, mainly SESA being key in this process. Hydropower is currently the main source of RE in CA and SA, followed by biofuels, notably bioethanol from sugarcane and biodiesel from soy. SESA is one of the main sources of production of the feedstocks for biofuels' production. Sugarcane and soy are likely to respond to the elevation of CO_2 and temperature with an increase in growth, which might lead to an increase in productivity and production. However, the drought effects expected for some regions in CA and SA will be critical and scientific knowledge has to advance in this area. Advances in second generation bioethanol from sugarcane and other feedstocks will be important as a measure of adaptation, as they have the potential to increase biofuels productivity in the region. In spite of the large amount of arable land available in the region, the expansion of sugarcane and soy, related to biofuels production, might have some indirect land use change effects, producing teleconnections that could lead to deforestation in the Amazon and loss of employment in some countries. This is especially derived from the expansion of soy, which is used for biodiesel production inclusively (27.3.6.).

Climate variability and climate change are negatively affecting human health in CA and SA, either by increasing morbidity, mortality, and disabilities (very high confidence), and through the emergence of diseases in regions previously non-endemic, or the re-emergence of diseases in areas where they have previously been eradicated or controlled (high confidence). Climate-related drivers have been recognized for respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), Hantaviruses and Rotaviruses, pregnancy-related outcomes, diabetes, chronic kidney diseases, and psychological trauma (27.3.7.1). Vulnerabilities vary with geography, age, gender, race, ethnicity, and socio-economic status, and are rising in large cities (27.3.7.2). It is very likely that Climate change and variability may exacerbate current and future risks to health, given the region's vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, and pollution.

The best way to be prepared to adapt to future climate change is by assisting people to cope with current climate variability. Long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the CA and SA population. Such conditions weaken the importance of adaptation planning to climate change on the political agenda. Various examples demonstrate possible synergies between development, adaptation and mitigation planning, which can help local communities and governments to allocate efficiently available resources in the design of strategies to reduce vulnerability (27.3.4, 27.4.1, 27.4.2, 27.4.3, 27.4.4, 27.5).

27.1. Introduction

27.1.1. The Central and South America Region

The CA and SA region harbours unique ecosystems and maximum biodiversity, has a variety of eco-climatic gradients, and it is rapidly developing. Agricultural and beef production is quickly increasing mostly by expanding agricultural frontiers; accelerated urbanization and demographic changes are remarkable; poverty and inequality are decreasing continuously, but at a low pace; while adaptive capacity is improving related to poverty alleviation.

The region has multiple stressors being climate variability/climate change and land cover change two of the most remarkable drivers of changes. Climate variability at various time scales has been affecting social and natural systems, and extremes in particular have affected large regions. During 2000-2010, almost 630 weather and climate extreme events ocurred in CA and SA, leaving near to 16,000 fatalities and 46.6 million people affected; and generating economical losses amounting to US$ 208 million (CRED, 2011). Land is facing increasing pressure from competing uses like cattle ranching, food production and bioenergy.

CA and SA are thought to have some key roles in the future because some countries, especially in SA, are rapidly developing and becoming economically important in the world scenario. The region is bound to be exposed to the pressure related to increasing land use and industrialization. Therefore, it is likely to have to deal with increasing emission potentials. Therefore, science-based decision-making is thought to be an important tool to control innovation and development of the countries in the region.

Two other important contrasting features characterize the region: having the biggest tropical forest of the planet on the one side, and possessing the largest potential for agricultural development during the next decades on the other. This is the case because the large countries of SA, especially, would have a major role in food and bioenergy production in the future, as long as policies towards adaptation to global climate change (GCC) will be strategically designed. The region is already one of the top producers and user of bioenergy and this experience will serve as an example to other developing regions as well as developed regions.

27.1.2. Summary of the AR4 and SREX Findings

27.1.2.1. AR4 Findings

During the last decades of the 20th century, unusual extreme weather events have been severely affecting the LA region contributing greatly to the strengthening of the vulnerability of human systems to natural disasters. In addition, increases in precipitation were observed in SESA, northwest Peru and Ecuador; while decreases were registered in southern Chile, southwest Argentina, southern Peru and western CA since 1960. Mean warming was near to 0.1ºC/decade. The rate of SLR has accelerated over the last 20 years reaching 2-3mm/year. The glacier-retreat trend has intensified, reaching critical conditions in the Andean countries. Rates of deforestation have been continuously increasing mainly due to agricultural expansion, and land degradation has been intensified for the entire region.

Mean warming for LA at the end of 21st century could reach 1ºC to 4ºC (SRES B2) or 2ºC to 6ºC (SRES A2). Rainfall anomalies (positive or negative) will be larger for the tropical part of LA.The frequency and intensity of weather and climate extremes is likely to increase.

Future impacts include: “Significant species extinctions, mainly in tropical LA” (high confidence). “Replacement of tropical forest by savannas, and semi-arid vegetation by arid vegetation” (medium confidence). “Increases in the number of people experiencing water stress” (medium confidence). “Probable reductions in rice yields and possible increases of soy yield in SESA; and increases in crop pests and diseases” (medium confidence). “Some coastal areas affected by sea level rise, weather and climatic variability and extremes” (high confidence).

Some countries have made efforts to adapt to climate change and variability, for example through the conservation of key ecosystems, the use of early warning systems and climate forecast, and the implementation of disease surveillance systems. However, several constraints like the lack of basic information, observation and monitoring systems; the lack of capacity-building and appropriate political, institutional and technological frameworks; low income; and settlements in vulnerable areas, outweigh the effectiveness of these efforts.

27.1.2.2. SREX Findings

As reported by the IPCC SREX (IPCC, 2012), a changing climate leads to changes in the frequency, intensity, spatial extent or duration of weather and climate extremes, and can result in unprecedented extremes. Levels of confidence in historical changes depend on the availability of high quality and homogeneous data, and relevant model projections. This has been a major problem in CA and SA, where a lack of long-term homogeneous and continuous climate and hydrological records, and of complete studies on trends have not allowed for an identification of trends in extremes, particularly in CA. Recent studies and projections from global and regional models suggest changes in extremes. With medium confidence, increases in warm days and decreases in cold days, as well as increases on warm nights and decreases in cold nights have been identified in CA, Northern SA, NEB, SESA and west coast of SA. In CA, there is low confidence that any observed long-term increase in tropical cyclone activity is robust, after accounting for past changes in observing capabilities. In other regions, such as the Amazon region, insufficient evidence, inconsistencies among studies and detected trends result in low confidence of observed rainfall trends. While it is likely that there has been an anthropogenic influence on extreme temperature in the region, there is low confidence in attribution of changes in tropical cyclone activity to anthropogenic influences.

Projections for the end of the 21st century for differing emissions scenarios (SRES A2 and A1B) show that for all CA and SA, models project substantial warming in temperature extremes. It is likely that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century on the global scale. With medium-high confidence, it is very likely that the length, frequency and/or intensity of heat waves will experience a large increase over most of SA, with weaker tendency towards increasing in SESA. With low to medium confidence, the models also project an increase of the proportion of total rainfall from heavy falls for SESA and the West coast of SA; while for Amazonia and the rest of SA and CA there are not consistent signals of change. In some regions, there is low confidence in projections of changes in fluvial floods. Confidence is low due to limited evidence and because the causes of regional changes are complex. There is medium confidence that droughts will intensify along the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration in Amazonia and NEB.

The character and severity of the impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. These are influenced by a wide range of factors, including anthropogenic climate change, natural climate variability, and socioeconomic development. Disaster risk management and adaptation to climate change focuses on reducing exposure and vulnerability and increasing resilience to the potential adverse impacts of climate extremes, even though risks cannot be fully eliminated.

27.2. Major Recent Changes and Projections in the Region

27.2.1. Climatic Stressors

27.2.1.1. Climate Trends, Long-term Variability, and Extremes

In CA and SA, decadal variability and changes in extremes have been affecting large sectors of the population, especially those more vulnerable and exposed to climate hazards. Observed changes in some regions have been attributed to natural climate variability while human influences (changes in extremes due to urbanization, for instance) have been attributed to land use change. Table 27-1 summarizes observed trends in the region's climate.

[INSERT TABLE 27-1 HERE
Table 27-1: Regional observed changes in temperature, precipitation and climate extremes in various sectors of CA and SA. Additional information on changes in observed extremes can be found in the IPCC SREX Chapter 3 (IPCC, 2012) and in WGI AR5 [2.4, 2.5, 2.6]]

Many areas in the Intra American Seas region that includes tropical and subtropical western North Atlantic Ocean encompassing the Gulf of Mexico, the Caribbean Sea, the Bahamas and Florida, the northeast coast of SA, and the juxtaposed coastal regions, including the Antillean Islands, show severe anomalies in rainfall. In CA and the North American Monsoon System (NAMS), rainfall has been starting increasingly later and has become more irregular in space and time, while the intensity of rainfall has been increasing during the onset season (see references in Table 27-1) since around 1950. Arias *et al*. (2012) found decadal rainfall variations in NAMS.

In SA, the West coast has shown a prominent but localized coastal cooling during the past 30-50 years extending from central Peru down to central Chile. Presumably, this occurs in connection with an increased upwelling of coastal waters favored by the trade winds (Narayan *et al*., 2010), that are associated with a negative trend in the sea surface temperature (SST) over a large oceanic region off the coast of northern Chile during the same period (Schulz *et al*., 2011). In the extremely arid northern coast of Chile, rainfall, temperature and cloudiness show strong interannual and decadal variability, and since the mid-70s, the minimum daily temperature, cloudiness and precipitation have decreased. In central Chile, a negative trend in precipitation was observed over the period 1935-1976, and an increase after 1976, while further south, the negative trend in rainfall that prevailed since the 1950s has intensified by the end of the 20th century (Quintana and Aceituno, 2012).

Towards the east of the Andes, NEB exhibits large interannual rainfall variability and a slight decrease since the 1970s. Although droughts in this region (e.g. 1983, 1987, 1998) have been associated with El Niño, the recent extremely intense drought in 2012-2013 occurred during La Niña (Marengo *et al*., 2013). In the La Plata Basin, various studies have documented interannual and decadal scale circulation changes that have led to decreases in the frequency of cold nights in austral summer, as well as to increases in warm nights and minimum temperatures during the last 40 years (see references in Table 27-1). Simultaneously, a reduction in the number of dry months in the warm season is found since the mid-1970s (see references in Table 27-1). Heavy rain frequency is increasing in SESA (references in Table 27-1).

In the central Andes, in the Mantaro Valley (Peru), precipitation shows a strong negative trend, while warming is also detected (SENAMHI, 2007). In the southern Andes of Peru, minimum air temperatures have increased during 1964-2006, while the number of frost days during September-April has also increased, but no clear signal on precipitation changes has been detected (Marengo *et al*., 2009a). In the northern Andes (Colombia, Ecuador), changes in temperature and rainfall in 1961-90 have been identified by Villacís (2008). In the Patagonia region, Masiokas *et al*. (2008) have identified an increase of temperature together with precipitation reductions during 1950-90.

For the Amazon basin, Marengo (2004), Marengo *et al*. (2009a; 2010), Satyamurty *et al*. (2010), and Buarque *et al*. (2010) concluded that no systematic unidirectional long-term trends towards drier or wetter conditions in both the northern and southern Amazon have been identified since the 1920s. Rainfall fluctuations are more characterized by inter-annual scales linked to ENSO or decadal variability. Analyzing a narrower time period, Espinoza *et al*. (2009a; 2009b) found that mean rainfall in the Amazon basin for 1964–2003 has decreased, with stronger amplitude after 1982, especially in the Peruvian western Amazonia (Lavado *et al*., 2012), consistent with reductions in convection and cloudiness in the same region (Arias *et al*., 2011). Recents studies by Donat *et al*. (2013) suggest that heavy rains are increasing in frequency in Amazonia. Regarding seasonal extremes in the Amazon region, two major droughts and three floods have affected the region from 2005 to 2012, although these events have been related to natural climate variability rather than to deforestation (Marengo *et al*., 2008; Espinoza *et al*., 2011; Lewis *et al*., 2011; Espinoza *et al*., 2012; Marengo *et al*., 2012a). On the impacts of land use changes on changes in the climate and hydrology of Amazonia, Zhang *et al*. (2009) suggest that biomass-burning aerosols can work against the seasonal monsoon circulation transition, thus re-inforce the dry season rainfall pattern for Southern Amazonia, while Wang *et al*. (2011) suggests the importance of deforestation and vegetation dynamics on decadal variability of

rainfall in the region. Costa and Pires (2010) have suggested a possible decrease in precipitation due to soybean expansion in Amazonia, mainly as a consequence of its very high albedo.

In the SAMS region in the last 50 or 60 years, positive trends in rainfall extremes have been identified (see Table 27-1). These studies suggest a pattern of increasing frequency and intensity of heavy rainfall events, with a tendency for early onsets and late demise of the rainy season.

Collini *et al*. (2008) and Saulo *et al*. (2010) find the SESA precipitation to be more responsive to changes in soil moisture, and although feedback mechanisms are present at all scales, the atmosphere influence is more significant at large scales. Moreover, land use change studies in the Brazilian southern Amazonia for the last decades showed that the impact on the hydrological response is time lagged at larger scales (Rodriguez *et al*., 2010)

27.2.1.2. Climate Projections

Since the AR4, substantial additional regional analysis has been carried out using the CMIP3 model ensemble. In addition, projections from CMIP5 models, and new experiences using regional models (downscaling) have allowed for a better description of future changes in climate and extremes in CA and SA. Using CMIP3 and CMIP5 models, Giorgi (2006), Diffenbaugh *et al*. (2008), Xu *et al*. (2009) and Diffenbaugh and Giorgi (2012) have identified areas of CA/western North America and the Amazon as persistent regional climate change hotspots throughout the 21st century of the RCP8.5 and RCP4.5. Table 27-2 summarizes projected climatic changes derived from global and regional models for the region, indicating the projected change, models, emission scenarios, time spans and references.

[INSERT TABLE 27-2 HERE
Table 27-2: Regional projected changes in temperature, precipitation, and climate extremes in different sectors of CA and SA. Various studies used A2 and B2 scenarios from CMIP3 and various RCPs scenarios for CMIP5, and different time slices from 2010 to 2100. In order to make results comparable, the CMIP3 and CMIP5 at the time slice ending in 2100 are included. Additional information on changes in projected extremes can be found in the IPCC SREX (see IPCC, 2012), and WG1 AR5 Chapter 9 and 14 [9.5, 9.6 and 14.2, 14.7]]

In CA and Northern Venezuela, projections from CMIP3 models and from downscaling expriments suggest precipitation reductions and warming together with an increase in evaporation, and reductions in soil moisture for most of the land during all seasons by the end of the 21th century (see references in Table 27-2). However, the spread of projections is high for future precipitation.

Analyses from global and regional models in tropical and subtropical SA show common patterns of projected climate in some sectors of the continent. Projections from CMIP3 regional and high resolution global models show by the end of the 21st century for a high emission scenario A2, a consistent pattern of increase of precipitation in SESA, Northwest of Peru and Ecuador and western Amazonia, while decreases are projected for northern SA, Eastern Amazonia, central eastern Brazil, NEB, the Altiplano and southern Chile (see references in Table 27-2). For some regions, projections show mixed results in rainfall projections, for the Amazonia and the SA monsoon region (see references in Table 27-2).

As for extremes, CMIP3 models and downscaling experiments show increases in dry spells are projected for Eastern Amazonia and NEB, while rainfall extremes are projected to increase in SESA, in western Amazonia, Northwest Peru and Ecuador, while over southern Amazonia, northeastern Brazil and eastern Amazonia, the maximum number of consecutive dry days tends to augment, suggesting a longer dry season. Increases in warm nights throughout SA are also rojected by the end of the 21st century (see references in Table 27-2). Shiogama *et al*. (2011) suggest that although the CMIP3 ensemble mean assessment suggested wetting across most of SA, the observational constraints indicate a higher probability of drying in the eastern Amazon basin.

The CMIP5 models project an even larger expansion of the monsoon regions in NAMS and SAMS in the future scenarios (Kitoh *et al*., 2012; Jones and Carvalho, 2013). A comparison from eight models from CMIP3 and CMIP5

identifies some improvements in the new generation models. For example, CMIP5 inter-model variability of temperature in summer was lower over northeastern Argentina, Paraguay and northern Brazil, in the last decades of the 21st century, as compared to CMIP3. Although no major differences were observed in both precipitation datasets, CMIP5 inter-model variability was lower over northern and eastern Brazil in summer by 2100 (Blázquez and Nuñez, 2012).

The projections from the CMIP5 models at regional level for CA and SA (using the same regions from the IPCC SREX) are shown in Figure 27-1, and update some of these previous projections based on SRES A2 and B2 emission scenarios from CMIP3. Figure 27-1 shows that in relation to the baseline period 1986-2005, for CA and northern South America-Amazonia, temperatures are projected to increase approximately by 1.8 °C and 3 °C for the RCP4.5 scenario, and by 4 C and 5 °C for the RCP8.5 scenario. For the rest of South America, increases by about 1.8 to 2 °C are projected for the RCP4.5 and by about 4 C to 5 C for the RCP8.5 scenario. The observed records show increases of temperature from 1900 to 1986 by about 1 °C. For precipitation, while for CA and northern South America-Amazonia precipitation is projected to decrease by about 10% (with large spread among models). For Northeast Brazil, there is a spread among models between +20 to -20% making hard to identify any projected change. This spread is much lower in the western coast of South America and SESA, where the spread is between +10 and -10%, and in SESA, the tendency is for an increase of precipitation that may reach 30%.

[INSERT FIGURE 27-1 HERE
Figure 27-1: Observed and simulated variations in past and projected future annual average temperature over land areas of the Central and South American "SREX regions". Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

27.2.2. Non-Climatic Stressors

27.2.2.1. Trends and Projections in Land Use and Land Use Change

Land use and land cover change are key drivers of environmental change for the region with significant impacts that may increase the potential negative impacts from climate change (Sampaio *et al*., 2007; Lopez-Rodriguez and Blanco-Libreros, 2008). The high levels of deforestation observed in most of the countries have been widely discussed in the literature as a deliberate development strategy based on the expansion of agriculture to satisfy the growing world demand for food, energy and minerals (Benhin, 2006; Grau and Aide, 2008; Mueller *et al*., 2008). Land is facing increasing pressure from competing uses, among them cattle ranching, food and bioenergy production. The enhanced competition for land increases the risk of land use changes, which may lead to negative environmental and socio-economic impacts. Agricultural expansion has relied in many cases on government subsidies, which have often resulted in lower land productivity and more land speculation (Bulte *et al*., 2007; Roebeling and Hendrix, 2010). Some of the most affected areas due to the expansion of the agricultural frontier are fragile ecosystems such as the edges of the Amazon forest in Brazil, Colombia, Ecuador and Peru, and the tropical Andes, where activities such as deforestation, agriculture, cattle ranching and gold mining are causing severe environmental degradation (ECLAC, 2010d), and the reduction of environmental services provided by these ecosystems.

Deforestation rates for the region remain high in spite of a reducing trend in the last decade (Ramankutty *et al*., 2007; Fearnside, 2008). Brazil is by far the country with the highest area of forest loss in the world according to the latest FAO statistics (2010): 21,940 km² per year -39% of world deforestation for the period 2005-2010. Bolivia, Venezuela and Argentina follow in deforested area (Figure 27-2) with all four countries accounting for 54% of the forest loss in the world for the same period. The countries of CA and SA lost a total of 38,300 km² of forest per year in that period (69% of the total world deforestation) (FAO, 2010). These numbers are limited by the fact that many countries do not have comparable information through time, particularly for recent years.

[INSERT FIGURE 27-2 HERE
Figure 27-2: Area deforested per year for selected countries in CA and SA (2005-2010). Notice three countries listed with a positive change in forest cover (based on data from FAO, 2010).]

Deforestation in the Amazon forest has received much international attention in the last decades, both because of its high rates, and its rich biodiversity. Brazilian Legal Amazon is now one of the best-monitored ecosystems in terms of deforestation since 1988 (INPE, 2011; see Figure 27-3). Deforestation rates for this region peaked in 2004 and have steadily declined since then currently exhibiting the lowest rates during the entire record. Such reduction results from a series of integrated policies to control illegal deforestation particularly enforcing protected areas, which now shelter 54% of the remaining forests of the Brazilian Amazon (Soares-Filho *et al.*, 2010). Deforestation in Brazilian Amazon for the period 2005-2010 accounted for 41% of the total deforestation for that country and showed the lowest rate for all forest biomes in Brazil (0.29%), with the Cerrado forest (drier ecosystem south of Amazon) presenting the forest biome with the highest deforestation rates (1.33%), accounting for 37% of Brazil's total deforestation (FAO, 2009).

[INSERT FIGURE 27-3 HERE
Figure 27-3: Deforestation rates in the Brazilian Amazonia (km^2/year) based on measurements by the PRODES INPE project (see also INPE, 2011).]

The amount of forest loss in CA is considerably less than in SA, owing to smaller country sizes. When deforestation rates are considered, Honduras and Nicaragua show the highest values for the area (Carr *et al.*, 2009). At the same time, CA includes three countries where forest cover shows a recovery trend in the last years: Costa Rica, El Salvador and Panama. This forest transition is the result of: (1) economies less dependent on agriculture, and more on industry and services (Wright and Samaniego, 2008); (2) processes of international migration with the associated remittances (Hecht and Saatchi, 2007), and (3) a stronger emphasis on the recognition of environmental services of forest ecosystems (Kaimowitz, 2008). The same positive trend is observed in some SA countries (Figure 27-2). However, a substantial amount of forest is gained through (single-crop) plantations, most noticeably in Chile (Aguayo *et al.*, 2009), which has a much lower ecological value than natural forests (Izquierdo *et al.*, 2008).

Land degradation, is also an important process compromising extensive areas of CA and SA very rapidly. According to data from the Global Land Degradation Assessment and Improvement (GLADA) project of the Global Environmental Facility (GEF), additional degraded areas reached 16.4% of the entire territory of Paraguay, 15.3% of Peru and 14.2% of Ecuador for the period 1982-2002. In CA, Guatemala shows the highest proportion of degraded land, currently at 58.9% of the country's territory, followed by Honduras (38.4%) and Costa Rica (29.5%); only El Salvador shows a reversal of the land degradation process, probably due to eased land exploitation following intensive migratory processes (ECLAC, 2010d).

Deforestation and land degradation are mainly attributed to increased extensive and intensive agriculture. Two activities have traditionally dominated the agricultural expansion: soy production (only in SA) and beef; but more recently, biomass for biofuel production has become as important (Nepstad and Stickler, 2008) with some regions also affected by oil and mining extractions. Deforestation by small farmers, mainly coming from families who migrate in search for land and using shifting agriculture techniques is relatively low. In this line, Oliveira *et al.* (2007) found that only 9% of the deforestation in the Peruvian Amazon between 1999 and 2005 happened in indigenous territories. Pasture for livestock production is the predominant land use in deforested areas of tropical and subtropical Latin America (Wassenaar *et al.*, 2007). More than 2/3 of the total deforested areas in Colombia (Etter *et al.*, 2006) and in the Brazilian Amazon (Nepstad *et al.*, 2006) are converted to cattle ranching. Forest conversion to pasture for livestock is also the major land use change driver in eastern Bolivia (Killeen *et al.*, 2008).

In recent years, soybean croplands have expanded continuously in SA, becoming increasingly more important in the agricultural production of the region. Soybean-planted area in Amazonian states (mainly Mato Grosso) in Brazil expanded 12.1% per year during the 1990s, and 16.8% per year from 2000 to 2005 (Costa *et al.*, 2007). This landscape-scale conversion from forest to soy and other large-scale agriculture can alter substantially the water

balance for large areas of the region resulting in important feedbacks to the local climate (Hayhoe *et al.*, 2011; Loarie *et al.*, 2011) (see section 27.3.4.1).

Soybean and beef production have also impacted other ecosystems next to the Amazon, such as the Cerrado (Brazil) and the Chaco dry forests (Bolivia, Paraguay, Argentina and Brazil). Gasparri *et al.* (2008) estimated carbon emissions from deforestation in Northern Argentina and concluded that deforestation in the Chaco forest has accelerated in the past decade from agricultural expansion and is now the most important source of carbon emission for that region. In northwest Argentina (Tucumán and Salta provinces) 1.4 Mha of dry forest were cleared from 1972 to 2007 as a result of technological improvements and increasing rainfall (Gasparri and Grau, 2009). Deforestation continued during the 1980s and 1990s resulting in cropland area covering up to 63% of the region by 2005 (Viglizzo *et al.*, 2011). In central Argentina (northern Córdoba province), cultivated lands have increased from 3% to 30% (between 1969 and 1999); and the forest cover has decreased from 52.5% to 8.2%. This change has also been attributed to the synergistic effect of climatic, socioeconomic, and technological factors (Zak *et al.*, 2008). Losses in the Atlantic forest are estimated in 29% of the original area in 1960, and in 28% of the Yunga forest area, mainly due to cattle ranching migration from the Pampas and Espinal (Viglizzo *et al.*, 2011).

Oil palm is a significant biofuel crop also linked to recent deforestation in tropical CA and SA. Its magnitude is still small compared with deforestation related to soybean and cattle ranching, but it is considerable for specific countries and expected to increase due to increasing demands for biofuels (Fitzherbert *et al.*, 2008). The main forest regions where oil palm has recently expanded are the Chocó region in Colombia and the Sucumbios region of Ecuador. Oil palm production is also important in Brazil (with 75% of the area planted in the state of Bahia) and emerging in the Amazonian region of Peru, where 72% of new plantations have expanded into forested areas (Gutiérrez-Vélez *et al.*, 2011).

However, forests are not the only important ecosystems threatened in the region. An assessment of threatened ecosystems in SA by Jarvis *et al.* (2010) concluded that grasslands, savannas and shrublands are more threatened than forests, mainly from fires and grazing pressure. An estimation of burned land in Latin America by Chuvieco *et al.* (2008) also concluded that, proportionally, the most affected ecosystems were the savannas of Colombia and Venezuela. In the Río de la Plata region (Central-East Argentina, southern Brazil, and Uruguay), grasslands decreased from 67.4% to 61.4% between 1985 and 2004. This reduction was associated with an increase in annual crops, mainly soybean, sunflower, wheat, and maize (Baldi and Paruelo, 2008).

Even with technological changes that might result in agricultural intensification, the expansion of pastures and croplands is expected to continue in the coming years (Wassenaar *et al.*, 2007; Kaimowitz and Angelsen, 2008), particularly fom an increasing global demand for food and biofuels (Gregg and Smith, 2010) with the consequent increase in commodity prices. This agricultural expansion will be mainly in Latin America and Sub-Saharan Africa as these regions hold two-thirds of the global land with potential to expand cultivation (Nepstad and Stickler, 2008). It is important to consider enforceable policy and legal reforms to keep this process of large-scale change under control as much as possible; these reforms should aim to reduce the impact on poor households who depend directly on the natural resources being depleted (Takasaki, 2007). Indigenous groups require particular attention in this respect; there is a growing acknowledgment that recognizing the land ownership and authority of indigenous groups can help central governments to better manage many of the natural areas remaining in the region (Oltremari and Jackson, 2006; Larson, 2010). Many indigenous groups are important drivers of land use change in the region and their well-being should be considered when designing responses to pressures on the land by a globalized economy (Gray *et al.*, 2008; Killeen *et al.*, 2008).

27.2.2.2. Trends and Projections in Socioeconomic Conditions

Development in the region has traditionally displayed four characteristics: low growth rates, high volatility, structural heterogeneity and a very unequal income distribution (ECLAC, 2008; Bárcena, 2010). This combination of factors has generated high and persistent poverty levels (45% for CA and 30% for SA for year 2010), with the rate of poverty being generally higher in rural than urban areas (ECLAC, 2009c). SA has based its economic growth in natural resource exploitation (mining, energy, agricultural), which involves direct and intensive use of land and

water, and in energy-intensive and, in many cases, highly polluting natural-resource-based manufactures. In turn, CA has exploited its proximity to the North American market and its relatively low labor costs (ECLAC, 2010e). The region shows a marked structural heterogeneity, where modern production structures coexist with large segments of the population with low productivity and income levels (ECLAC, 2010g). The GDP per capita in SA is twice that of CA; in addition, in the latter poverty is 50% higher (see Figure 27-4).

[INSERT FIGURE 27-4 HERE
Figure 27-4: Evolution of GDP per capita and poverty (income below US$ 2 per day) from 1990-2011: CA and SA (US-Dollars per inhabitant at 2005 prices and percentages) (ECLAC on the basis of CEPALSTAT (2012)and ECLAC (2011c))]

The 2008 financial crisis reached CA and SA through exports and credits, remittances and worsening expectations by consumers and producers (Bárcena, 2010; Kacef and López-Monti, 2010). This resulted in the sudden stop of six consecutive years of robust growth and improving social indicators, which contributed to higher poverty in 2009 after six years where poverty had declined by 11%. Poverty rates fell from 44% to 33% of the total population, leaving 150 million people in this situation while extreme poverty diminished from 19.4% to 12.9% (which represents slightly more than 70 million people) (ECLAC, 2010e).

In the second half of 2009 industrial production and exports began to recover and yielded a stronger economic performance (GDP growth of 6.4% in SA and 3.9% in CA in 2010) (ECLAC, 2012). SA benefited the most because of the larger size of their domestic markets and the greater diversification of export markets. Conversely, slower growth was observed in CA with more open economies and a less diversified portfolio of trading partners and a greater emphasis on manufacturing trade (ECLAC, 2010g).

The region is expected to continue to grow in the short term, albeit at a pace that is closer to potential GDP growth, helped by internal demand as the middle class becomes stronger and as credit becomes more available. In SA, this could be boosted by external demand from the Asian economies as they continue to grow at a rapid pace. The macroeconomic challenge is to act counter cyclically creating conditions for productive development that is not based solely on commodity exports (ECLAC, 2010f).

In spite of its economic growth, the region still displays high and persistent inequality: most countries have Gini coefficients between 0.5 and 0.6, whereas the equivalent figures in a group of 24 developed countries vary between under 0.25 and around 0.40. The average per capita income of richest 10% of households is approximately 17 times that of the poorest 40% of households. Nevertheless, during the first decade of the century, prior to the financial crisis, the region has shown a slight but clear trend towards a more equitable distriburion of income and a stronger middle class population resulting in a higher demand for goods (ECLAC, 2010g; UN, 2010; ECLAC, 2011b). Latin American countries also reported gains in terms of human development, although these gains have slowed down slightly over recent years. In comparative terms, the performance of countries as measured by the Human Development Index (HDI) varied greatly (from Chile with 0.878 and Argentina with 0.866 to Guatemala -0.704- and Nicaragua -0.699-) although those with lower levels of HDI showed notably higher improvements than countries with the highest HDI (UNDP, 2010).

Associated with inequality are disparities in access to water, sanitation and adequate housing for the most vulnerable groups - for example indigenous peoples, Afro-descendants, children and women living in poverty- and in their exposure to the effects of climate change. The strong heterogeneity of subnational territorial entities in the region takes the form of high spatial concentration and persistent disparities in the territorial distribution of wealth (ECLAC, 2010g; UN, 2010; ECLAC, 2011b).

The region faces significant challenges in terms of environmental sustainability and adaptability to a changing climate (UN, 2010), reflecting the specific characteristics of its population and economy already discussed and added to a significant deficit in infrastructure development. The stakeholders - the State, private sector and civil society- have made progress in incorporating environmental protection into decision-making processes, and particularly in terms of environmental institutions and legislation. Difficulties, however, remain in effectively mainstreaming the environment into public policies (UN, 2010). While the global economic and financial crises

together with climate change impose new challenges, they also provide an opportunity to shift development and growth patterns towards a more environmentally friendly economy.

27.3. Impacts, Vulnerabilities, and Adaptation Practices

27.3.1. Freshwater Resources

CA and SA are regions with a high average but unevenly distributed water resources availability (Magrin *et al.*, 2007a). The main user of water is agriculture, accounting for 70% of all withdrawals used to feed more than 20 Mha of irrigated land (14% of the world's total cultivated area) (ECLAC *et al.*, 2010). The second use is composed by the region's 580 million inhabitants (including the Caribbean), of which 86% had access to water supply by 2006 (ECLAC, 2010b), although in rural areas only 51% of the population have access to those services. In terms of non-consumptive water uses, according to the International Energy Agency (IEA), the region meets 60% of its electricity demand through hydropower generation, which contrast with the 20% average contribution of other regions (see case study 27.6.1).

27.3.1.1. Observed and Projected Impacts

In CA and SA there are many evidences of changing conditions in terms of hydro-geophysical variables (cryosphere and runoff) that affect streamflow and finally water availability.

The most robust trend for major rivers is found in the sub-basins of the La Plata River basin (***high agreement, robust evidence***). This basin, second only to the Amazon in size, and third in streamflow (21,500 m^3/s) (Pasquini and Depetris, 2007), shows a positive trend in streamflow in the second half of the 20th century at different sites (Pasquini and Depetris, 2007; Krepper *et al.*, 2008; Saurral *et al.*, 2008; Amsler and Drago, 2009; Conway and Mahé, 2009; Dai *et al.*, 2009; Krepper and Zucarelli, 2010a; Dai, 2011; Doyle and Barros, 2011). An increase in precipitation and a reduction in evapotranspiration from land use changes have been associated with the trend in streamflows (Saurral *et al.*, 2008; Doyle and Barros, 2011), with the former being more important in the southern sub-basins and the latter in the northern ones (Doyle and Barros, 2011) (see section 27.2.1). Increasing trends in streamflows have also been found in the Laguna Mar Chiquita (a closed lake), and in the Santa Fe Province, both in Argentina, with ecological and erosive consequences (Pasquini *et al.*, 2006; Rodrigues Capítulo *et al.*, 2010; Troin *et al.*, 2010; Venencio and García, 2011; Bucher and Curto, 2012). The effect of reservoirs on changing hydrologic conditions has been reported for the San Francisco River basin in Northeast Brazil (Andrade e Santos *et al.*, 2012; Genz and Luz, 2012).

There is no clear long-term trend for the Amazon River, owing to its strong interannual and decadal variability. Extremely low levels were experienced during the droughts of 2005 and 2010, while record high levels for the same rivers were detected during the 2009 and 2012 floods (see section 27.2.1). Espinoza *et al.* (2009a; 2011) showed that the 1974-2004 apparent stability in mean discharge at the main stem of the Amazon in Obidos is explained by opposing regional features of Andean rivers (e.g. increasing trends in the Peruvian Amazons, Lavado *et al.*, 2012) (see section 27.2.1). Major Colombian rivers draining to the Caribbean Sea (Magdalena and Cauca) exhibit decreasing trends along their main channels (Carmona and Poveda, 2011), while significant trends are absent for all other major large rivers in the Brazilian North East, and northern SA (Dai *et al.*, 2009). The only study done for rivers in CA is that of Dai (2011) who showed a drying trend in this region.

Water resources are threatened by the rapid retreat and melting of the Andean cryosphere, which has been further reported following the IPCC AR4, through diverse techniques such as aereal photography, satellite imagery, ice coring, and lichens in the tropical glaciers of Venezuela, Colombia, Ecuador, Peru and Bolivia (see reviews in Vuille *et al.*, 2008a ; Jomelli *et al.*, 2009; Bradley *et al.*, 2009; Poveda and Pineda, 2009; Rabatel *et al.*, 2012) and specific papers in Table 27-3a). A synthesis of the studies recognizes with ***high confidence*** (based on ***high agreement, and robust evidence***) that tropical glaciers' retreat has accelerated since the middle of the 20th century (Table 27-3a). In early stages of glacier retreat runoff tends to increase due to an acceleration of glacier melt, but after a peak in

discharge as the glacierized water reservoir gradually empties, runoff tends to decrease, as evidenced in the Cordillera Blanca of Peru (Chevallier *et al*., 2011; Baraer *et al*., 2012), where seven out nine river basins have probably crossed a critical threshold, exhibiting a decreasing dry-season discharge (Baraer *et al*., 2012). In general, runoff tends to decrease during the period in the year when precipitation is at its lowest level. Likewise, glaciers and icefields in the extra tropical Andes located in Central-South Chile and Argentina face significant reductions (see Table 27-3b), with their effect being compounded by changes in snowpack extent, thus magnifying changes in hydrograph seasonality by reducing flows in dry seasons and increasing them in wet seasons.

[INSERT TABLE 27-3 HERE
Table 27-3: Observed trends related to Andean cryosphere.
a) Andean tropical glacier trends since the Little Ice Age (LIA) maximum and, particularly, during the last decades
b) Extra tropical Andean cryposphere (glaciers, snowpack, runoff effects) trends]

Some regions in Central-South Chile and Argentina also face significant reductions in precipitation (section 27.2.1), which has contributed to runoff reductions in the last decades of the 20th century (Seoane and López, 2007; Rubio-Álvarez and McPhee, 2010; Urrutia *et al*., 2011), contrasted with long-term trends found through dendrochronology (Lara *et al*., 2007; Urrutia *et al*., 2011). Trends in precipitation and runoff are less evident in the Central-North region in Chile (Fiebig-Wittmaack *et al*., 2012; Souvignet *et al*., 2012).

Assessment on future impacts (see Table 27-4) show a large range of uncertainty across the spectrum of climate models. It is hard to make conclusive statements in terms of trends on some particular regions/rivers. Nohara *et al*. (2006) studied climate change impacts on 24 of the main rivers in the world (considering an uncertainty analysis driven by use of 19 GCMs), and found no robust change for the Paraná (La Plata Basin) and Amazon Rivers. Nevertheless, in both cases the average change showed a positive value consistent at least with observations for the La Plata Basin. On top of such climatic uncertainty, future streamflows and water availability projections are confounded by the potential effects of deforestation (Moore *et al*., 2007; Coe *et al*., 2009).

[INSERT TABLE 27-4 HERE
Table 27-4: Synthesis of projected climate change impacts on hydrologic variables in large South American basins and major glaciers.]

CA shows a consistent runoff reduction, Maurer *et al*. (2009) studied climate change projections for the Lempa River basin, one of the largest basins in CA, covering portions of Guatemala, Honduras and El Salvador. They showed that future climate projections imply a reduction of 20% in inflows to major reservoirs in this system (see Table 27-4). Imbach *et al*. (2012) found similar results using a modeling approach that also considered potential changes in vegetation. These effects could have large hydropower generation implications as discussed in the case study (see section 27.6.1).

Since the AR4 several studies have been developed to associate future climate scenarios with the evolution of glaciers, especially in the tropical Andes. Juen *et al*. (2007) and Chevallier *et al*. (2011) developed "regression" type of analysis relating glacier evolution (manifested as downstream streamflow) to changes in temperature. Similarly, Poveda and Pineda (2009) performed linear extrapolations on historic glacier retreat rates to estimate the fate of the six remaining glaciers in Colombia. In general, these studies indicate that glaciers may continue their retreat (Vuille *et al*., 2008a) as glacier Equilibrium Line Altitudes rises, with larger hydrological effects during the dry season (Kaser *et al*., 2010; Gascoin *et al*., 2011). This is expected to happen during the next 20-50 years (Juen *et al*., 2007; Chevallier *et al*., 2011) (see Table 27-4). After that period water availability during the dry months is expected to diminish. A forecast, for instance, by Baraer *et al*. (2012) for the Santa River in the Peruvian Andes finds that once the glaciers are completely melt, annual discharge would decrease by 2%–30%, depending on the watershed.

Significant effects are foreseen in the energy balances of the Andes, through changes in temperature and albedo, thus influencing hydrologic regimes. In Central Chile, Vicuña *et al*. (2011) project changes in the seasonality of streamflows of the upper snowmelt-driven watersheds of the Limarí River, associated with temperature increases and reductions in water availability owing to a reduction (increase) in precipitation (evapotranspiration) (see Table 27-4). Similar conclusions are derived across the Andes on the Limay River in Argentina by Seoane and López

(2007). Projected changes in the cryosphere conditions of the Andes could affect the occurrence of extreme events, such as the Glacial-lake outburst floods occurring in the icefields of Patagonia (Dussaillant *et al.*, 2010), volcanic collapse and debris flow associated with accelerated glacial melting in the tropical Andes (Carey, 2005; Carey *et al.*, 2012b; Fraser, 2012), and with volcanoes in southern Chile and Argentina (Tormey, 2010), as well as scenarios of water quality pollution by exposure to contaminants owing to glaciers retreat (Fortner *et al.*, 2011).

27.3.1.2. Vulnerability and Adaptation Practices

Vulnerability for the region considers both 'future/outcome vulnerability' (related to impacts associated with climate change) and 'actual/contextual vulnerability' (depending on social, political, economic, cultural, and institutional factors) (O'Brien *et al.*, 2007). Current highly vulnerable regions include the semi-arid regions in Chile-Argentina and North East Brazil, certain regions in CA, and communities along the tropical Andes.

Semiarid regions are characterized by pronounced climatic variability and often by water scarcity and related social stress (Krol and Bronstert, 2007; Scott *et al.*, 2012). The semiarid regions of Central Chile-Argentina are expected to face streamflow reductions and changes in seasonality, with potentially significant effects on already vulnerable and highly populated regions (e.g. Santiago, Chile) and extensive agriculture irrigation demands (ECLAC, 2009a; Souvignet *et al.*, 2010; Fiebig-Wittmaack *et al.*, 2012). The need to develop special adaptation tools to face the threats of climate change is particularly special for the most vulnerable communities in this region (Young *et al.*, 2010), such as those located in the transition between the semiarid and arid climates (Debels *et al.*, 2009) (see Table 27-4).

Another semiarid region that has been studied thoroughly is the Northeast Brazilian (Hastenrath, 2012). De Mello *et al.* (2008), Gondim *et al.* (2008), Souza *et al.* (2010) and Montenegro and Ragab (2010) have shown that future climate change scenarios would decrease water availability for agriculture irrigation owing to reductions in precipitation and increases in evapotranspiration. Krol and Bronstert (2007) and Krol *et al.* (2006) presented an integrated modeling study that linked projected impacts on water availability for agriculture with economic impacts that could potentially drive full-scale migrations in the Brazilian northeast region.

In CA, Benegas *et al.* (2009), Manuel-Navarrete *et al.* (2007) and Aguilar *et al.* (2009) provide different frameworks to understand vulnerability and adaptation strategies to climate change and variability in urban and rural contexts, although no specific adaptation strategies are suggested.

The retreat of Andean glaciers can exacerbate water resources vulnerability (Bradley *et al.*, 2006; Casassa *et al.*, 2007; Vuille *et al.*, 2008b; Mulligan *et al.*, 2010). Glacier retreat diminishes the mountains' water regulation capacity, making it more expensive and less reliable the supply of water for diverse purposes, as well as for ecosystems integrity (Buytaert *et al.*, 2011). Impacts on economic activities associated with conceptual scenarios of glacier melt reduction have been monetized (Vergara *et al.*, 2007), representing about US$100 million in the case of water supply for Quito, and between US$212 million to US$ 1.5 billion in the case of the Peruvian electricity sector due to losses of hydropower generation (see case study 27.6.1). Andean communities face an important increase in their vulnerability, as documented by Mark *et al.* (2010), Pérez *et al.* (2010) and Buytaert and De Bièvre (2012). Different issues have been addressed in the assessment of adaptation strategies for these communities such as the role of governance and institutions (Young and Lipton, 2006; Lynch, 2012), technology (Carey *et al.*, 2012a), and the dynamics of multiple stressors (McDowell and Hess, 2012).

A series of policies have been developed to reduced vulnerability to climate variability as faced today in different regions and settings of CA and SA. In 1997, Brazil instituted the National Water Resources Policy and created the National Water Resources Management System under the shared responsibility between the States and the Federal government. Key to this new regulation has been the promotion of decentralization and social participation through the creation of National Council of Water Resources and their counterparts in the states, the States Water Resources Councils. The challenges and opportunities dealing with water resources management in Brazil in the face of climate variability and climate change have been well studied (Abers, 2007; Kumler and Lemos, 2008; Medema *et al.*, 2008; Engle *et al.*, 2011; Lorz *et al.*, 2012). Other countries in the region are following similar approaches. In the last five

years, there have been constitutional and legal reforms towards more efficient and effective water resources management and coordination among relevant actors in Honduras, Nicaragua, Ecuador, Peru, Uruguay, Bolivia and Mexico; although in many cases, these innovations have not been completely implemented (Hantke –Domas, 2011). Institutional and governance improvements are required to assure an effective implementation of these adaptation measures (e.g. Halsnæs and Verhagen, 2007; Engle and Lemos, 2010; Lemos *et al*., 2010; Zagonari, 2010; and Pittock, 2011).

The particular experience in Northeast Brazil provides other examples of adaptation strategies. Broad *et al*. (2007) and Sankarasubramanian *et al*. (2009) studied the potential benefits of streamflow forecast in this region as a way to reduce the impacts of climate change and climate variability on water distribution under stress conditions. An historical review and analysis of drought management in this region are provided by Campos and Carvalho (2008). Souza Filho and Brown (2009) studied different water distribution policy scenarios finding that the best option depended on the degree of water scarcity. The study by Nelson and Finan (2009) provides a critical perspective of drought-related policies, arguing that they constitute an example of maladaptation as they do not try to solve the causes of vulnerability and instead undermine resilience. Tompkins *et al*. (2008) are also critical of risk reduction practices in this region because they have fallen short of addressing the fundamental causes of vulnerability needed for efficient longer-term drought management.

Other types of adaptation options that stem from studies on arid and semiarid regions are related to: a) increase in water supply from groundwater pumping (Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010; Burte *et al*., 2011); fog interception practices (Holder, 2006; Klemm *et al*., 2012), and reservoirs and irrigation infraestructure (Fry *et al*., 2010; Vicuña *et al*., 2010; 2012); b) improvements in water demand management associated with increased irrigation efficiency and practices (Geerts *et al*., 2010; Montenegro and Ragab, 2010; Van Oel *et al*., 2010; Bell *et al*., 2011; Jara-Rojas *et al*., 2012), and changes towards less water intensive crops (Montenegro and Ragab, 2010).

Flood management practices also provide a suite of options to deal with actual and future vulnerabilities related to hydrologic extremes, such as the management of ENSO-related events in Peru via participatory (Warner and Oré, 2006) or risk reduction approaches (Khalil *et al*., 2007), the role of land use management (Bathurst *et al*., 2010; 2011; Coe *et al*., 2011), and flood hazard assessment (Mosquera-Machado and Ahmad, 2006).

27.3.2. Terrestrial and Inland Water Systems

27.3.2.1. Observed and Projected Impacts and Vulnerabilities

CA and SA house the largest biological diversity and several of the world's megadiverse countries (Mittermeier *et al*., 1997; Guevara and Laborde, 2008). However, land use change has led to the existence of six biodiversity hotspots, i.e. places with a great species diversity that show high habitat loss and also high levels of species endemism: Mesoamerica, Chocó-Darien-Western Ecuador, Tropical Andes, Central Chile, Brazilian Atlantic forest, and Brazilian Cerrado (Mittermeier *et al*., 2005). Thus, conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss in the region (Ayoo, 2008). Tropical deforestation is the second largest driver of anthropogenic climate change on the planet, adding up to 17%-20% of total greenhouse gas emissions during the 1990s (Gullison *et al*., 2007; Strassburg *et al*., 2010). In parallel, the region has still large extensions of wilderness areas for which the Amazon is the most outstanding example. Nevertheless, some of these areas are precisely the new frontier of economic expansion. For instance, between 1996 and 2005 Brazil deforested about 19,500 km^2 per year, which represented 2% to 5% of global annual CO_2 emissions (Nepstad *et al*., 2009). Between 2005 and 2009, deforestation in the Brazilian Amazon dropped by 36%, which is partly related to the network of protected areas that now covers around 45.6% of the biome in Brazil (Soares-Filho *et al*., 2010). Using LandSHIFT modeling framework for land use change and the IMPACT projections of crop/livestock production, Lapola *et al*. (2011) projected that zero deforestation in the Brazilian Amazon forest by 2020 (and of the Cerrado by 2025) would require either a reduction of 26%–40% in livestock production until 2050 or a doubling of average livestock density from 0.74 to 1.46 head per hectare. Thus, climate change may imply reduction of yields and entail further deforestation.

Local deforestation rates or rising greenhouse gases globally drive changes in the regional SA that during this century might lead the Amazon rainforest into crossing a critical threshold at which a relatively small perturbation can qualitatively alter the state or development of a system (Cox *et al*., 2000; Salazar *et al*., 2007; Sampaio *et al*., 2007; Lenton *et al*., 2008; Nobre and Borma, 2009). Various models are projecting a risk of reduced rainfall and higher temperatures and water stress, that may lead to an abrupt and irreversible replacement of Amazon forests by savanna-like vegetation, under a high emission scenario (A2), from 2050-2060 to 2100 (Betts *et al*., 2004; Cox *et al*., 2004; Salazar *et al*., 2007; Sampaio *et al*., 2007; 2008; Malhi *et al*., 2008; Sitch *et al*., 2008; Malhi *et al*., 2009; Nobre and Borma, 2009; Marengo *et al*., 2011c). The possible 'savannization' or 'die-back' of the Amazon region would potentially have large-scale impacts on climate, biodiversity and people in the region. The possibility of this die-back scenario occurring, however, is still an open issue and the uncertainties are still very high (Rammig *et al*., 2010; Shiogama *et al*., 2011).

Plant species are rapidly declining in CA, SA, Central and West Africa, and Southeast Asia (Bradshaw *et al*., 2009). Risk estimates of plant species extinction in the Amazon, which do not take into account possible climate change impacts, range from 5%-9% by 2050 with a habitat reduction of 12%-24% (Feeley and Silman, 2009) to 33% by 2030 (Hubbell *et al*., 2008). The highest percentage of rapidly declining amphibian species occurs in CA and SA. Brazil is among the countries with most threatened bird and mammal species (Bradshaw *et al*., 2009).

A similar scenario is found in inland water systems. Among the components of aquatic biodiversity, fish are the best-known organisms (Abell *et al*., 2008) with Brazil accounting for the richest icthyofauna of the planet (Nogueira *et al*., 2010). For instance, the 540 Brazilian small microbasins host 819 fish species with restrict distribution. However, 29% of these microbasins have historically lost more than 70% of their natural vegetation cover and only 26% show a significant overlap with protected areas or indigenous reserves. Moreover, 40% of the microbasins overlap with hydrodams (see 27.6.1 and Chapter 3) or have few protected areas and high rates of habitat loss (Nogueira *et al*., 2010).

The faster and more severe the rate of climate change, the more severe the biological consequences such as species decline (Brook *et al*., 2008). Vertebrate fauna in North and South America is projected to suffer species losses until 2100 of at least 10%, as forecasted in over 80% of the climate projections based on low emissions scenario (Lawler *et al*., 2009). Vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains for emission scenarios varying from low B1 to mid-high A2 (Lawler *et al*., 2009). Elevational specialists, i.e. a small proportion of species with small geographic ranges restricted to high mountains, are most frequent in the Americas (e.g. Andes and Sierra Madre) and might be particularly vulnerable to global warming because of their small geographic ranges and high energetic and area requirements, particularly birds and mammals (Laurance *et al*., 2011). In Brazil, projections for Atlantic forest birds (Anciães and Peterson, 2006), endemic bird species (Marini *et al*., 2009), and plant species (by 2055, scenarios HHGSDX50 and HHGGAX50; Siqueira and Peterson, 2003) of the Cerrado indicate that distribution will dislocate towards the South and Southeast, precisely where fragmentation and habitat loss are worse. Global climate change is also predicted to increase negative impacts worldwide, including SA, on freshwater fisheries due to alterations in physiology and life histories of fish (Ficke *et al*., 2007).

In addition to climate change impacts at individual species level, biotic interactions will be affected. Modifications in phenology, structure of ecological networks, predator-preys interactions and non-trophic interactions among organisms have been forecasted (Brooker *et al*., 2008; Walther, 2010). The outcome of non-trophic interactions among plants is expected to shift along with variation in climatic parameters, with more facilitative interactions in more stressful environments, and more competitive interactions in more benign environments (Brooker *et al*., 2008; Anthelme *et al*., 2012). These effects are expected to have a strong influence of community and ecosystem (re-) organization given the key engineering role played by plants on the functioning of ecosystems (Callaway, 2007). High Andean ecosystems, especially those within the tropics, are expected to face exceptionally strong warming effects during the 21th century because of their uncommonly high altitude (Bradley *et al*., 2006). At the same time they provide a series of crucial ecosystem services for millions people (Buytaert *et al*., 2011). For these reasons shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in this region.

Although in the region biodiversity conservation is largely confined to protected areas, with the magnitude of climatic changes projected for the century, it is expected that many species and vegetational types will lose representativeness inside such protected areas (Heller and Zavaleta, 2009).

27.3.2.2. Adaptation Practices

The sub-set of practices that are multi-sectoral, multi-scale, and based on the premise that ecosystem services reduce the vulnerability of society to climate change are known as Ecosystem-based Adaptation (EbA) (Vignola *et al.*, 2009; see also Glossary). Schemes such as the payment for environmental services (PES) and community management fit the concept of EbA that begins to spread in CA and SA (Vignola *et al.*, 2009). The principle behind these schemes is the valuation of ecosystem services that should reflect both the economic and cultural benefits derived from the human-ecosystem interaction and the capacity of ecosystems to secure the flow of these benefits in the future (Abson and Termansen, 2011).

Since PES schemes have developed more commonly in CA and SA than in other parts of the world (Balvanera *et al.*, 2012), this topic will be covered as a case study (see 27.6.2 in this Chapter).

Ecological restoration can be an important tool for adaptation. A meta-analysis of 89 studies by Benayas *et al.* (2009) (with timescale of restoration varying from <5 to 300 years), including many in SA, showed that ecological restoration enhances the provision of biodiversity and environmental services by 44% and 25%, respectively, as compared to degraded systems (Benayas *et al.*, 2009) Moreover, ecological restoration increases the potential for carbon sequestration and promotes community organization, economic activities and livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon *et al.*, 2011; Rodrigues *et al.*, 2011). Chazdon *et al.* (2009) also highlight the potential of restoration efforts to build ecological corridors (see Harvey *et al.*, 2008, for example in Central America).

Community management of natural areas is another efficient tool to adapt to climate change and to reconcile biodiversity conservation with socio-economic development. Porter-Bolland *et al.* (2012) compared protected areas with areas under community management in different parts of the tropical world, including CA and SA, and found that protected areas have higher deforestation rates than areas with community management. Similarly, Nelson and Chomitz (2011) found for the region that (i) protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and that (ii) in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas. This somehow contrasts with the findings of Miteva *et al.* (2012) that found protected areas more efficient in constraining deforestation than other schemes. Other good examples of adaptive community management in the continent include community forest concessions (e.g., Guatemala; Radachowsky *et al.*, 2012), multiple-use management of forests (Guariguata *et al.*, 2012 ; see also examples in Brazil – Klimas *et al.*, 2012, Soriano *et al.*, 2012, and Bolívia – Cronckleton *et al.*, 2012); and local communities where research and monitoring protocols are in place to pay the communities for collecting primary scientific data (Luzar *et al.*, 2011).

27.3.3. Coastal Systems and Low-Lying Areas

27.3.3.1. Observed and Projected Impacts and Vulnerabilities

Climate change is altering coastal and marine ecosystems (Hoegh-Guldberg and Bruno, 2010). Coral reefs, seagrass beds, mangroves, rocky reefs and shelves, and seamounts have few to no areas left in the world that remain unaffected by human influence (Halpern *et al.*, 2008). Anthropogenic drivers associated with climate change decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and greater incidence of disease (Hoegh-Guldberg and Bruno, 2010). Coastal and marine impacts and vulnerability are often associated with collateral effects of climate change such as sea-level rise, ocean warming and ocean acidification. Overfishing, habitat pollution and destruction, and the invasion of species also negatively impact biodiversity and the delivery of ecosystem services (Guarderas *et al.*, 2008; Halpern *et al.*, 2008).

Such negative impacts lead to losses that pose significant challenges and costs for societies, particularly in developing countries (Hoegh-Guldberg and Bruno, 2010). For instance, the Ocean Health Index (Halpern *et al.*, 2012) that measures how healthy the coupling of the human-ocean system is for every coastal country (including parameters related to climate change), indicates that CA countries rank amongst the lowest values. For SA, Suriname stands out with one of the highest scores.

Since the coastal states of Latin America and the Caribbean have a human population of more than 610 million, 3/4 of whom live within 200 km of the coast, marine ecosystems have been undergoing significant transformations (Guarderas *et al.*, 2008). Fish stocks, places for recreation and tourism, and controls of pests and pathogens are all under threat (Guarderas *et al.*, 2008; Mora, 2008). Moreover, changes over 2 mm yr^{-1} of sea-level rise have been found in CA and SA. The Western equatorial border, influenced by the ENSO phenomenon, shows a lower variation (of about 1 mm yr^{-1}) and a range of variation under El Niño events of the same order of magnitude that the sustained past changes. The distribution of population is a crucial factor for inundation impact, with coastal areas being non-homogeneously impacted. A scenario of 1m SLR would affect some coastal populations in Brazil and the Caribbean islands (see Figure 27-5). (ECLAC, 2011a)

[INSERT FIGURE 27-5 HERE
Figure 27-5: Current and predicted coastal impacts and coastal dynamics in response to climate change (elaborated by Iñigo Losada, ECLAC)]

The greatest flooding levels (hurricanes not considered) in the region are found in Rio de La Plata area, which combine a 5 mm yr^{-1} change in storm surge with SLR changes in extreme flooding levels (ECLAC, 2011a). Extreme flooding events may become more frequent since return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected, while at the same time beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast. (ECLAC, 2011a)

The majority of literature concerning climate change impacts for coastal and marine ecosytems consideres coral reefs, mangroves and fisheres. Coral reefs are particularly sensitive to climate-induced changes in the physical environment (Baker *et al.*, 2008) to an extent that 1/3 of the more than 700 species of reef-building corals worldwide are already threatened with extinction (Carpenter *et al.*, 2008). Coral bleaching and mortality are often associated with ocean warming and acidification (Baker *et al.*, 2008). If extreme sea surface temperatures are to continue, the projections of scenario SRES A1F indicate that it is possible that the Mesoamerican coral reef will collapse by mid-century, causing major economic losses (Vergara *et al.*, 2009). Extreme high sea surface temperatures have been increasingly documented in the western Caribbean near the coast of CA and have resulted in frequent bleaching events (1993, 1998, 2005, and again in 2010) of the Mesoamerican coral reef, located along the coasts of Belize, Honduras and Guatemala (Eakin *et al.*, 2010). Reef but also mangrove ecosystems are estimated to contribute greatly to goods and services in economic terms. In Belize, for example, this amount is approximately US$395-US$559 million annually, primarily through marine-based tourism, fisheries and coastal protection (Cooper *et al.*, 2008). In the Eastern Tropical Pacific, seascape trace abundance of cement and elevated nutrients in upwelled waters are factors that help explain high bioerosion rates of local coral reefs (Manzello *et al.*, 2008). In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years. Francini-Filho *et al.* (2008) pointed out that coral diseases intensified between 2005 and 2007 based on qualitative observations since the 1980s and regular monitoring since 2001. They have also predicted that *Mussismilia braziliensis*- a major reef-building coral species that is endemic in Brazil- will be nearly extinct in less than a century if the current rate of mortality due to disease is not reversed (Francini-Filho *et al.*, 2008).

Mangroves are largely affected by anthropogenic activities whether or not they are climate driven. All mangrove forests, along with important ecosystem goods and services, could be lost in the next 100 years if the present rate of loss continues (1-2% a year) (Duke *et al.*, 2007). Moreover, estimates are that climate change may lead to a maximum global loss of 10–15% of mangrove forest by 2100 (Alongi, 2008). In CA and SA, some of the main drivers of loss are deforestation and land conversion, agriculture and shrimp ponds (Polidoro *et al.*, 2010). The Atlantic and Pacific coasts of CA are some of the most endangered in the planet with regards to mangroves, since approximately 40% of the present mangroves' species are threatened with extinction (Polidoro *et al.*, 2010). Approximately 75% of the mangrove extension of the planet is concentrated in 15 countries, among which Brazil is

included (Giri *et al*., 2011). The rate of survival of original mangroves lies between 12.8% and 47.6% in the Tumaco Bay (Colombia), resulting in ecosystem collapse, fisheries reduction and impacts on livelihoods (Lampis, 2010). Gratiot *et al*. (2008) project for the current decade an increase of mean high water levels of 6 cm followed by 90m shoreline retreat implying flooding of thousands of hectares of mangrove forest along the coast of French Guiana.

Peru and Colombia are two of the eight most vulnerable countries to climate change impacts on fisheries, due to the combined effect of observed and projected warming, the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities (Allison *et al*., 2009). Fisheries production systems are already pressured by overfishing, habitat loss, pollution, invasive species, water abstraction and damming (Allison *et al*., 2009). In Brazil, a decadal rate of 0.16 trophic level decline has been detected through most of the northeastern coast, between 1978 and 2000, which is one of the highest rates documented in the world (Freire and Pauly, 2010).

Despite the focus in the literature on corals, mangroves and fisheries, there is evidence that other benthic marine invertebrates that provide key services to reef systems, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change (Przeslawski *et al*., 2008). The same applies for seagrasses for which a worldwide decline has accelerated from a median of 0.9% yr^{-1} before 1940 to 7% yr^{-1} since 1990, which is comparable to rates reported for mangroves, coral reefs, tropical rainforests and place seagrass meadows among the most threatened ecosystems on earth (Waycott *et al*., 2009).

A major challenge of particular relevance at local and global scales will be to understand how these physical changes will impact the biological environment of the ocean (e.g., Gutiérrez *et al*., 2011b), as the Humboldt Current system -flowing along the west coast of SA- is the most productive upwelling system of the world in terms of fish productivity.

27.3.3.2. Adaptation Practices

Designing marine protected areas (MPAs) that are resilient to climate change is a key adaptation strategy in coastal and marine environments (McLeod *et al*., 2009). By 2007, Latin America and the Caribbean (which includes CA and SA countries) had over 700 MPAs established covering around 1.5% of the coastal and shelf waters, most of which allow varying levels of extractive activities (Guarderas *et al*., 2008). This protected area cover, however, is insufficient to preserve important habitats or connectivity among populations at large biogeographic scales (Guarderas *et al*., 2008).

In Brazil, a protected area type known as “Marine Extractive Reserves” currently benefits 60,000 small-scale fishermen along the coast (Moura *et al*., 2009). Examples of fisheries’ co-management, a form of a participatory process envolving local fishermen communities, government, academia and NGOs, are reported to favor a balance between conservation of marine fisheries, coral reefs and mangroves on the one hand (Francini-Filho and Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations on the other (Moura *et al*., 2009; Hastings, 2011).

In addition to marine protected areas that include mangroves and functionally linked ecosystems, Gilman *et al*. (2008) list a number of other relevant adaptation practices: coastal planning to facilitate mangrove migration with sea-level rise, management of activities within the catchment that affect long-term trends in the mangrove sediment elevation, better management of non-climate stressors, and the rehabilitation of degraded areas.

Significant financial and human resources are expended annually in the marine reserves to support reef management efforts. These actions, including the creation of marine reserves to protect from overfishing, improvement of watershed management, and protection or replanting of coastal mangroves, are proven tools to improve ecosystem functioning. However, they may also actually increase the thermal tolerance of corals to bleaching stress and thus the associated likelihood of surviving future warming (Carilli *et al*., 2009).

Adaptations to sea level rise involve redirecting new settlements to better-protected locations and to promote investments in appropriate infrastructure. This shall be required in the low elevation coastal zones (LECZ) of the region, particularly in lower income countries with limited resources, which are especially vulnerable. The same applies to countries with high shares of land (e.g., Brazil ranking 7th worldwide of the total land area in the LECZ) and/or population (e.g., Guyana and Suriname rank 2nd and 5th by the share of population in the LECZ, having respectively 76% and 55% of their populations in such areas (McGranahan *et al*., 2007). Adaptation will demand effective and enforceable regulations and economic incentives, all of which require political will as well as financial and human capital (McGranahan *et al*., 2007).

27.3.4. Food Production Systems and Food Security

27.3.4.1. Observed and Projected Impacts and Vulnerabilities

Increases in the global demand for food, forage, fiber and biofuels promoted a sharp increase in agricultural production in SA and CA mainly associated with the expansion of planted areas (see Chapter 7). This trend is predicted to continue since SA accounts for 40% of the global potential arable land (Nellemann *et al*., 2009). Agro-ecosystems are being and will be affected in isolation and synergistically by climate variability/change and land use changes, which are comparable drivers of environmental change. According to projections based on 30 GCMs (under SRES A1B and B1) by the end of 21th century (2070-2099), SA could lose between 1% and 21% of its arable land due to climate change and population growth (Zhang and Cai, 2011).

In the future, SA will face both the great challenge of fulfilling the growing food and biofuels demand and the impact of climate change, trying to preserve natural resources. Although optimal land management could combine efficient agricultural and biofuels production with ecosystem preservation under climate change conditions, current practices are far from optimal, leading to a deterioration of ecosystems throughout the continent (see section 27.3.2). Examples for this are, e.g., in southern Brazilian Amazonia water yields were near four times higher in soy than forested watersheds, and showed greater seasonal variability (Hayhoe *et al*., 2011). In the Argentinas Pampas current land use changes disrupt water and biogeochemical cycles and may result in soil salinization, altered C and N storage, surface runoff and stream acidification (Nosetto *et al*., 2008; Berthrong *et al*., 2009; Farley *et al*., 2009). In central Argentina flood extension was associated with the dynamics of groundwater level that, in turn, has been influenced by precipitation and land use change (Viglizzo *et al*., 2009).

Observed impacts: The SESA region has shown significant increases in precipitation and wetter soil conditions during the 20th century (Giorgi, 2002) (see Table 27-1). Rainfall increases benefited summer crops and pastures productivity, and contributed to a significant expansion of agricultural areas, mainly in climatically marginal regions of Argentina (Barros, 2010; Hoyos *et al*., 2012). Comparing the periods 1930-60 and 1970-2000, maize and soybean yields increased between 9% and 58% in Argentina, Uruguay and South Brazil (Magrin *et al*., 2007b) mainly due to precipitation increases. However, current agricultural production systems, which evolved partially in response to wetter conditions, could be threatened if climate reverts to a drier situation, putting at risk the the viability of continuous agriculture in marginal regions of the Argentina's Pampas (Podestá *et al*., 2009). During the 1930s-1940s, dry and windy conditions together with deforestation, overgrazing, overcropping and non-suitable tillage technology produced devastating results including severe dust storms, cattle mortality, crop failure, farmer bankruptcy and rural migration (Viglizzo and Frank, 2006).

At the global scale, warming since 1981 has reduced wheat, maize and barley productivity, although the impacts were small compared with the technological yield gains over the same period (Lobell and Field, 2007). In central Argentina, simulated potential wheat yield has been decreasing at increasing rates since 1930 (1930-2000: -28 kg/ha/year; 1970-2000: -53 kg/ha/year) in response to increases in minimum temperature during October-November (1930-2000: +0.4°C/decade; 1970-2000: +0.6°C/decade) (Magrin *et al*., 2009). Lobell *et al*. (2011) showed that the observed changes in the growing season temperature and precipitation between 1980 and 2008 have slowed the positive yield trends due to improved genetics in Brazilian wheat, maize and soy, as well as Paraguayan soy. In contrast, rice in Brazil and soybean in Argentina have benefited from precipitation and temperature trends. In

Argentina, increases in soybean yield may be associated with weather types that reduce thermal stress during flowering and pod set stages and favour stability at harvest time (Bettolli *et al*., 2009).

Projected impacts: In SESA climate change could benefit some crops until mid-21st-century if CO_2 effects are considered (see Table 27-5), although interannual and decadal climate variability coul provoke important damages. In Uruguay, productivity could increase steadily until the 2030s-2050s depending on the SRES scenario.(ECLAC, 2010c). In Argentina average yields of soy, maize and wheat could increase or remain almost stable. Increases in temperature and precipitation may benefit crops towards the southern and western zone of the Pampas (Magrin *et al*., 2007c; ECLAC, 2010c). In South Brazil, irrigated rice yield (Walter *et al*., 2010) and bean productivity (Costa *et al*., 2009) is expected to increase. If technological improvement is considered, the productivity of common bean and maize could increase between 40% and 90% (Costa *et al*., 2009). Sugarcane production could benefit as warming could allow the expansion of planted areas towards the south, where low temperatures are a limiting factor (Pinto *et al*., 2008). Increases in crop productivity could reach 6% in São Paulo state towards 2040 (Marin *et al*., 2009). In Paraguay the yields of soybean and wheat could remain almost stable or increase slightly until 2030 (ECLAC, 2010a).

In Chile and western Argentina, yields could be reduced by water limitation. In central Chile (30ºS to 42ºS) temperature increases, reduction in chilling hours and water shortages may reduce productivity of winter crops, fruits, vines and radiata pine. Conversely, rising temperatures, more moderate frosts and more abundant water will *very likely* benefit all species towards the South (Meza and Silva, 2009; ECLAC, 2010a). In northern Patagonia (Argentina) fruit and and vegetable growing could be negatively affected because of a reduction in rainfall and in average flows in the Neuquén River basin. At the same time in the region, in specific in the north of the Mendoza basin, increases in water demand, because of population growth, may compromise the availability of subterranean water for irrigation, pushing up irrigation costs and forcing many producers out of farming towards 2030. Also, water quality could be reduced by the worsening of existing salinization processes (ECLAC, 2010a).

In CA, northeastern Brazil and parts of the Andean region (Table 27-5) climate change could affect crop yields, local economies and food security. Results from 23 GCMs suggest a high probability (>90%) that growing season temperatures in parts of tropical SA, east of the Andes and CA will exceed the extreme seasonal temperatures documented from 1900 to 2006 at the end of this century, affecting regional agricultural productivity and human welfare (Battisti and Naylor, 2009). For NEB, declining crop yields in subsistence crops such as beans, corn and cassava are projected (Lobell *et al*., 2008; Margulis *et al*., 2010). In addition, increases in temperature could reduce the areas currently favorable to cowpea bean (Silva *et al*., 2010). The warming up to 5.8 °C foreseen for 2070 could make the coffee crop unfeasible in Minas Gerais and São Paulo (SE Brazil) if no adaptation action is accomplished. By 2070 the coffee crop may have to be transferred to southern regions where frost risk will be much lower (Camargo, 2010). A Great increases in Arabica coffee production (principally in the Uruguayan border and North of Argentina) are expected in low climatic risks areas with 3ºC increases in mean temperature (Zullo *et al*., 2011). Brazilian potato production could be restricted to a few months in currently warm areas, which today allow potato production all around the year (Lopes *et al*., 2011). Large losses of suitable environments for the “Pequi” tree (*Caryocar brasiliense*; an economically important Cerrado fruit tree) are projected by 2050, mainly affecting the poorest communities in Central Brazil (Nabout *et al*., 2011). Climate change in the Amazon region may also have a critical impact on the yields of commonly cultivated crops. Lapola *et al*. (2011) showed that by 2050 soybean yields would be reduced by 44% in the worst-case scenario (HadCM3 climate and no CO_2 fertilization).

Teixeira *et al*. (2011) identified hot spots for heat stress towards 2071-2100 under the A1B scenario and suggest that rice in South East Brazil, maize in CA and SA, and soybean in Central Brazil will be the crops and zones most affected by increases in temperature.

In CA, warming conditions combined with more variable rainfall are expected to reduce maize, bean and rice productivity endangering the food security of many people and increasing poverty (ECLAC, 2010c) (see Table 26-7). According to Lobell *et al*. (2008), rice and wheat yields could decrease up to 10% by 2030. In Panamá, maize production could modestly increase over the century because of accelerated development helping the grain-filling period to be completed before the worst water stresses occur, although the large interannual climate variations will continue to be the dominant influence on seasonal maize yield into the coming decades (Ruane *et al*., 2011).

One of the uncertainties associated with the impacts of climatic change is the effect of CO_2 on plant physiology. According to DaMatta *et al.* (2010), many crops (such as soybean, common bean, maize and sugarcane) can probably respond with an increasing productivity as a result of higher growth rates and better water use efficiency. However, food quality could decrease due to higher sugar contents in grain and fruits, and decreases in the protein content in cereals and legumes.

Uncertainties associated with climate and crop models, as well as with the uncertainty in human behavior, potentially lead to large error bars on any long-term prediction of food output. However, the trends presented here represent the current available information (see Table 27-5).

[INSERT TABLE 27-5 HERE
Table 27-5: Impacts on agriculture.]

Climate change may also alter the current scenario of plant diseases and their management, having effects on productivity (Ghini *et al*., 2011). In Argentina, years with severe infection of late cycle diseases in soybean could increase; severe outbreaks of the Mal de Rio Cuarto virus in maize could be more frequent; and wheat head fusariosis will increase slightly in the south of the Pampas region, and decrease in the north by the end of the century (ECLAC, 2010a; Martínez *et al*., 2011). Potato late blight (*Phytophtora infestans*) severity is expected to increase in Perú (Giraldo *et al*., 2010). However, there is uncertainty related to how plants will respond to diseases because of a potential increase in plants' photosynthesis and accelerates in their metabolism under the effect of elevated CO_2 and higher temperature (Sage, 2002), possibly offsetting many of the diseases' effects in the future.

The impacts of climate change on livestock production would vary by species and climate scenarios. By 2060, under a hot and dry scenario, beef and dairy cattle, pigs and chickens could decrease between 0.9 and 3.2%, while sheep could increase by 7% mainly in the Andean mountain countries. Dairy cattle could increase only in Uruguay and Argentina. Under a milder and wetter scenario, beef cattle choice declines in Colombia, Ecuador, and Venezuela, but increases in Argentina and Chile. Sheep increase in Colombia and Venezuela, but decrease in the high mountains of Chile where chickens are chosen more frequently Seo *et al.* (2010). Future climate could strongly affect milk production and feed intake in dairy cattle in Brazil. Furthermore, substantial modifications in the Brazilian areas at present suitable for livestock, particularly in the main Pernambuco region are expected (Silva *et al*., 2009).

Climate change impact on regional welfare will depend not only on changes in yield, but also in international trade. By 2030, global cereal price could change between +32% (low-productivity scenario) and -16% (optimistic yield scenario). A rise in prices could benefit net exporting countries like Brazil, where gains from terms of trade shifts could outweigh the losses due to climate change. Despite experiencing significant negative yield shocks, some countries tend to gain from higher commodity prices (Hertel *et al*., 2010). Increases in prices during 2007-2009 led to rising poverty in Nicaragua, but decreasing poverty in Peru (see chapter 7).

27.3.4.2. Adaptation Practices

Genetic advances and suitable soil and technological management may induce an increase in some crops' yield despite unfavorable future climate conditions. In Argentina, genetic techniques, specific scientific knowledge and land-use planning are viewed as promising sources of adaptation (Urcola *et al*., 2010). Adjustments in sowing dates and fertilization rates could reduce negative impacts in maize and wheat crops in Argentina and Chile (Magrin *et al*., 2009; Meza and Silva, 2009; Travasso *et al*., 2009b). Furthermore, in central Chile and southern Pampas in Argentina warmer climates could allow performing two crops per season increasing productivity per unit land (Monzon *et al*., 2007; Meza *et al*., 2008). In Brazil, adaptation strategies for coffee crops include: planting at high densities, vegetated soil, accurate irrigation and breeding programs, and shading management system (arborization) (Camargo, 2010). Shading is also used in Costa Rica and Colombia. In South Brazil, a good option for irrigated rice could be to plant early cultivars (Walter *et al*., 2010).

Several adaptation practices have been oriented towards water management (see section 27.3.1), especially in irrigated crops for a needed better preparedness regarding water scarcity. Adaptive strategies might need to look at the harvest, storage, temporal transfer and efficient use of rainfall water (Quiroga and Gaggioli, 2011). Adaptation to water scarcity can be improved by taking into account a well-known set of agronomic practices like: fallowing, crop sequences, groundwater management, no-till operations, cover-crops and fertilization. Deficit irrigation could be an effective measure for water savings in dry areas such as the Bolivian Altiplano (quinoa), central Brazil (tomatoes) and northern Argentina (cotton) (Geerts and Raes, 2009).

The best way to be prepared to adapt to future climate change is by assisting people to cope with current climate variability (Baethgen, 2010), for which the use of climatic forecasts in agricultural planning presents a measure. Increased access to scientific forecasts, and increased availability of improved forecast information would greatly enhance the ability of the farmers in the Brazilian Amazon to cope with El Niño events (Moran *et al*., 2006). Other climatic indices such as the SOI (Southern Oscilation Index) for maize and the SSTSA (Sea Surface Temperature South Atlantic) for soybean and sunflower were the best indicators of annual crop yield variability in Argentina (Travasso *et al*., 2009a). Another possibility to cope with extreme events, consists in transferring weather-related risks by using different types of rural insurance (Baethgen, 2010). Index insurance is one mechanism that has been recently introduced to overcome obstacles to traditional agricultural and disaster insurance markets (see chapter 15). For the support of such a parametric agricultrual insurance, a Central American climate data base was recently established (CRRH-SICA, 2010).

Local and indigenous knowledge have the potential to bring solutions even in the face of rapidly changing climatic conditions (Folke *et al*., 2002; Alteri and Koohafkan, 2008), Crop diversification is used in the Peruvian Andes to suppress pest outbreaks and dampen pathogen transmission (Lin, 2011). In Honduras, Nicaragua and Guatemala traditional practices such as soil and water conservation, cover cropping, organic fertilizer and integrated pest management have proven more resilient to erosion and runoff and have helped retain more topsoil and moisture during periods of droughts (Holt-Gimenez, 2002). A case study with indigenous farmers in highland Bolivia indicates that constraints on access to key resources must be addressed for reducing vulnerability over time (McDowell and Hess, 2012). Otherwise, adaptation measures may include an orientation towards non-farming activites as was the case for NEB. In that case, vulnerability has been increasing since the late 1990s due mainly to the overuse of natural resources to which smallholders responded with off-farm activities to sustain their livelihoods (Sietz, 2011). In El Salvador, if local sustainability efforts continue the future climate vulnerability index could only slightly increase by 2015 (Aguilar *et al*., 2009).

Shifting in agricultural zoning has been an autonomous adaptation observed in SA. In Argentina e.g., increases in precipitation promoted the expansion of the agricultural frontier to the West and North of the traditional agricultural area, resulting in environmental damage that could be aggrevated in the future (Barros, 2007; República Argentina, 2007). Adjustment of production practices, like farmers in the semi-arid zones of mountain regions of Bolivia have begun as they noticed strong changes in the climate since the 1980s, including upward migration of crops, selection of more resistant varieties and water capturing, presents a further adaptation measure (PNCC, 2007).

Organic systems are highly adaptive to climate change due to the application of traditional skills and farmers' knowledge, soil fertility-building techniques and a high degree of diversity (ITC, 2007). A controversial, but important issue in relation to adaptation is the use of genetically modified plants to produce food, with biotech crops being likely to be key to cope with the needed food productivity increase considiering global population trend (see Chapter 7) Brazil and Argentina are the 2nd and 3rd fastest growing biotech crop producers in the world after the US (Marshall, 2012).

Two of the main challenges to maintain food quality and food security in most regions of the world will be 1) the integration of agriculture based in breeding and biotech with organic strategies and 2) the integration between food and bioenergy production. These two issues have to be addressed by increasing the production of scientific knowledge in agriculture, which according to Nivia *et al*. (2009) in CA and SA is the one that receive the lowest investments when compared to the rest of the world.

27.3.5. Human Settlements, Industry, and Infrastructure

According to the World Bank database (The World Bank, 2012) CA and SA are the geographic regions with the second largest urbanization rate (79%), only behind North America (82%) and clearly above the world average (50%). It is therefore of high relevance the assessment of the literature on climate change impacts and vulnerability of *urban* human settlements in this region as presented in this section. The information provided should be complemented with other sections of the chapter (see 27.2.2.2; 27.3.1; 27.3.3; and 27.3.7)

27.3.5.1. Observed and Projected Impacts and Vulnerabilities

Urban human settlements suffer from many of the vulnerabilities and impacts already presented in several sections of this chapter. The provision of critical resources and services as already discussed in the chapter –water, health and energy– and of adequate infrastructure and housing remain factors of urban vulnerability *likely* to be enhanced by climate change (Smolka and Larangeira, 2008; Winchester, 2008; Roberts, 2009; Romero-Lankao, 2012).

Water resource management for example (see section 27.3.1), is a major concern for many cities in view of both controlling flooding while retaining water for other uses (Henríquez Ruiz, 2009). More than 20% of the population in the region tends to be concentrated in the largest city of each country (The World Bank, 2012), and hence water availability for human consumption in the region's megacities (e.g. São Paulo, Santiago, Lima, Buenos Aires) is of great concern. In this regards, reduction in glacier and snowmelt related runoff in the Andes poses important adaptation challenges for many cities, e.g. the metropolitan areas of Lima, La Paz/El Alto and Santiago de Chile (Bradley *et al*., 2006; Hegglin and Huggel, 2008; Melo *et al*., 2010). The excess of water is also a preoccupation in several cities. In São Paulo for example, according to Marengo *et al*. (2009b; 2012b) the number of days with rainfall above 50 mm were almost absent during the 1950s and now they occur between 2 to 5 times per year (2000-2010). The increase in precipitation is one of the expected vulnerability issues affecting the city of São Paulo as presented in Box 27-1. Increases in flood events during 1980-2000 have been observed also in the Buenos Aires province and Metropolitan Area (Andrade and Scarpati, 2007; Barros *et al*., 2008; Hegglin and Huggel, 2008; Nabel *et al*., 2008). There are also the combined effects of climate change impacts, human settlements' features and other stresses, such as more intense pollution events (Moreno, 2006; Nobre *et al*., 2011; Nobre, 2011; Romero-Lankao *et al*., 2013b) and more intense hydrological cycles from urban heat-island effects.

_____START BOX 27-1 HERE_____

Box 27-1. Vulnerability of South American Megacities to Climate Change: The Case of the Metropolitan Region of São Paulo (MRSP)

Research in the Metropolitan Region of São Paulo (MRSP), between 2009 and 2011, reveals a very comprehensive and interdisciplinary project on the impacts of climate variability and change, and vulnerability of Brazilian megacities. Studies derived from this project (Nobre *et al*., 2011; Marengo *et al*., 2012b) identify the impacts of climate extremes on the occurrence of natural disasters and the impacts on human health. These impacts are linked to a projected increase of 38% in the extension of the urban area of the MRSP by 2030, accompanied by a projected increase in rainfall extremes. These may induce an intensification of urban flash floods and land slides, affecting larges areas of the population that is already vulnerable to climate extremes and variability. The urbanization process in the MRSP has been affecting the local climate, and the intensification of the heat island effect to a certain degree may be responsible for the 2°C warming detected in the city during the last 50 years (Nobre *et al*., 2011). This warming has been further accompanied by an increase in heavy precipitation as well as more frequent warm nights (Marengo *et al*., 2012b; Silva Dias *et al*., 2012). By 2100, climate projections based on data from 1933-2010 show an expected warming between 2-3°C in the MRSP, together with a possible doubling of the number of days with heavy precipitation in comparison to the present (Marengo *et al*., 2012b; Silva Dias *et al*., 2012).

With the projected changes in climate and in the extension of the MRSP (Marengo *et al*., 2012b) more than 20% of the total area of the city could be potentially affected by natural disasters. Related, more frequent floods may increase the risk of leptospirosis, which together with increasing air pollution and worsening environmental

conditions that trigger the risk of respiratory diseases would leave the population of the MRSP more vulnerable. Potential adaptation measures include a set of strategies needed to be developed by the MRSP and its institutions to face environmental changes. Among them are a better building control to avoid construction in risk areas, investment in public transportation, protection of the urban basins and the establishment of forest corridors in the collecting basins and slope regions. The lessons learned suggest that the knowledge on the observed and projected environmental changes, as well as on the vulnerability of populations living in risk areas is of great importance on the definition of adaptation policies as a first step towards improving the quality of life and building resilient cities in Brazil.

_____END BOX 27-1 HERE_____

Changes in prevailing urban climates have led to changing patterns of disease vectors, also water-borne disease issues linked to water availability and subsequent quality (see section 27.3.7). The influence of climate change on particulate matter and other local contaminants is also relevant in this regard (Moreno, 2006). The relationship between the two factors – water and disease – is important to highlight given the on-going problems of water stress, also intense precipitation events. Both give rise to changing disease risks, as well as wider problems of event-related mortalities and morbidity, and infrastructure and property damage. For low-income groups concentrated in settlements with little or no service provision, e.g. waste collection, piped drinking water, sanitation, these risks are compounded (ECLAC, 2008). Existing cases of flooding, air pollution and heat waves reveal that not only low-income groups are at risk, but also that wealthier sectors are not spared. Factors such as high-density settlement (Barros *et al.*, 2008) and the characteristics of some hazards explain this – e.g., poor and wealthy alike are at risk from air pollution and temperature in Santiago de Chile and Bogota (Romero-Lankao *et al.*, 2012; 2013b).

There are also other climate change risks in terms of economic activity location and impacts on urban manufacturing and service workers, e.g. thermal stress (Hsiang, 2010), and the forms of urban expansion or sprawl into areas where ecosystem services may be compromised and risks enhanced, e.g. floodplains. Both processes are also related to rising motorisation rates; the number of light vehicles in Latin America and the Caribbean is expected to double between 2000 and 2030, and be three times the 2000 figure by 2050 (ECLAC, 2009b).

While urban populations face diverse social, political, economic and environmental risks in daily life, climate change adds a new dimension to these risk settings (Pielke Jr *et al.*, 2003; Roberts, 2009; Romero-Lankao and Qin, 2011). Since urban development remains fragile in many cases, with weak planning responses, climate change is *likely* to compound existing challenges. The probabilities and magnitudes of these events in each urban center will differ signigicantly according to socioeconomic, institutional and physical context.

27.3.5.2. Adaptation Practices

Given high regional urbanization rates in CA and SA, the direct (e.g. flooding, heat islands) and indirect effects (e.g. food insecurity, watershed management) of climate change present an urban set of challenges and opportunities for mainstreaming flood management, warning systems and other adaptation responses with sustainability goals (Bradley *et al.*, 2006; Hegglin and Huggel, 2008; Hardoy and Pandiella, 2009; Romero-Lankao, 2012; Romero-Lankao *et al.*, 2013a).

Increasingly the links between adaptation and a wide variety of local development issues are being highlighted and brought into urban and regional planning in SA and CA. These issues include connections with natural hazards and risk assessment, disease transmission, resource availability, land use considerations, poverty linked to vulnerability, and with appropriate governance frameworks. (Barton, 2009; Luque *et al.*, 2013)

Population, economic activities and authorities have a long experience of responding to climate related hazards, particularly through disaster risk management (e.g., Tucuman and San Martin, Argentina (Plaza and Pasculi, 2007; Sayago *et al.*, 2010)) and land use and economic develop planning to a limited extent (Barton, 2009). Climate policies can build on these. Several adaptation plans have been generated over the last five years in São Paulo, Buenos Aires, Quito, Esmeraldas, Santiago and other large cities (Romero-Lankao, 2007b; Carmin *et al.*, 2009;

Romero-Lankao, 2012; Luque *et al*., 2013; Romero-Lankao *et al*., 2013a). Local administrations participate in the ICLEI, C40 and other networks demonstrating their engagement towards climate resilient cities. In smaller settlements, there is lower capacity to respond (e.g., climate change and vulnerability information (Hardoy and Romero-Lankao, 2011). These policies, plans and programs are required to reduce social vulnerability, and identify and reduce potential economic effects of climate on the local economy. Rio de Janeiro, for example, with its coastline property and high dependence on tourists (and their perceptions of risk), cannot ignore these climate related hazards (Gasper *et al*., 2011).

Poverty and vulnerability, as interlinked elements of the adaptation challenge in CA and SA, remain pivotal to understanding urban responses and provoke the need for 'pro-poor' responses that engage with broader development issues and not solely the capacity to respond to climate change (Hardoy and Pandiella, 2009; Winchester and Szalachman, 2009; Hardoy and Romero-Lankao, 2011). These broader links are part of the complexity of defining and operationalizing vulnerability concepts, and the need to develop these alongside more dominant infrastructural responses to adaptation, as with mitigation (Romero-Lankao, 2007a; Romero-Lankao and Qin, 2011). Within these response options, a focus on social assets has been highlighted by Rubin and Rossing (2012), rather than a, purely, physical asset focus.

Much urbanisation involves in-migrating or already resident, low-income groups and their location in risk-prone zones (Costa Fereira *et al*., 2011). The need to consider land use arrangements, particularly risk-prone zones, as part of climate change adaptation have highlighted the role of public space in order to increase vegetation, thus mitigate the heat island effect, also to reduce risks from landslides and flooding (Rodríguez Laredo, 2011).

In the case of governance frameworks, there is clear evidence that incorporation of climate change considerations into wider city planning is still a challenge, as are more inter-sectoral and participative processes that have been linked to more effective policies (Barton, 2009; De Oliveira, 2009; Romero-Lankao *et al*., 2013a). Several metropolitan adaptation plans have been generated over the last five years, although these have been largely restricted to the largest conglomerations, and are included as an addition to principally mitigation plans, e.g. São Paulo and Buenos Aires.

27.3.6. Renewable Energy

27.3.6.1. Observed and Projected Impacts and Vulnerabilities

Table 27-6 shows the relevance of RE in the Latin America energy matrix as compared to the world for 2009 according to the International Energy Agency statistics (IEA, 2012). Hydropower is the most representative source of RE in the region and therefore analyzed separately from this section and all other RE sources (see case study in section 27.6.1.). At the same time, geothermal energy will be not discussed as it is assumed that there is no impact of climate change on the effectiveness of this energy type (Arvizu *et al*., 2011).

[INSERT TABLE 27-6 HERE
Table 27-6: Comparison of consumption of different energetics in Latin America and the world (in thousand tonnes of oil equivalent (ktoe) on a net calorific value basis).]

Lucena *et al*. (2009) demonstrated that hydro and wind energy, as well as biodiesel production might be particularly sensitive to climate change in Brazil. With the vital role that RE plays in mitigating the effects of GCC, this sensitivity translates into the importance of accounting with knowledge on the implementation of RE projects as well as on the crops providing bioenergy, being by far the most important sources of non-hydro RE in SA and CA.

For historical reasons, CA and SA developed sugarcane as bioenergy feedstock, as sugarcane has been considered advantageous for its high sugar contents. Brazil accounts for the most intensive RE production in the form of bioethanol, which is used by 90% of the cars in the country (Goldemberg, 2008) whereas biodiesel comprises 5% of all diesel nationwide. In 2011, countries like Colombia and Chile have started efforts to increase their bioenergy production from sugarcane and eucalyptus, respectively. With the continent's long latitudinal length, the expected

impacts of climate changes on plants are very complex due to a wide variety of climate conditions, imposing the problem of using different crops in different regions. For biodiesel, in Brazil 80% is produced from soybeans, but there are promising new sources such as the African palm dendê (Lucena *et al*., 2009). As mentioned in the section 27.2.2, the development of palm oil as well as soybean are important factors that induce land use change, with a potential to influence stability of forests in certain key regions in SA, such as the Amazon.

Biofuels are promising sources of RE that can help CA and SA to decrease emissions from energy production and use. At the same time, RE might imply potential problems such as those related to positive net emissions of greenhouse gases, threats to biodiversity, an increase in food prices and competition for water resources (see also 27.2.3), some of which can be reverted or attenuated (Koh and Ghazoul, 2008). For example, the sugarcane agro industry in Brazil, besides producing bioethanol, combusts the bagasse to produce electricity, in a process called cogeneration, providing power for the bioethanol industry and increasing sustainability. The excess heat energy is then used to generate bioelectricity, thus allowing the biorefinery to be self-sufficient in energy utilization (Amorim *et al*., 2011; Dias *et al*., 2012). In 2005/2006 the production of bioelectricity was estimated to be 9.2 kWh per ton of sugarcane (Macedo *et al*., 2008), approximately 2% of Brazil's total energy generation production.

Most bioenergy feedstocks at present in production in CA and SA are grasses. In the case of sugarcane, the responses to the elevation of CO_2 concentration up to 720ppmv have been shown to be positive in terms of biomass production and principally regarding water use efficiency (Souza *et al*., 2008).

The production of energy from renewable sources such as hydro- and wind power are greatly dependent on climatic conditions and therefore may be impacted in the future by GCC. The analysis by Lucena *et al*. (2010a), related to liquid biofuels and hydropower, suggests an increasing energy vulnerability of the poorest regions of Brazil to GCC together with a possible negative influence on biofuels production and electricity generation, mainly biodiesel and hydropower respectively.

Expansion of biofuel plantations in Brazil might cause both direct and indirect land use changes (e.g., biofuel plantations replacing rangelands, which previously replaced forests) with the direct land use changes, according to simulation performed by Lapola *et al*. (2010) of the effects for 2020. The same study shows that sugarcane ethanol and biodiesel derived from soybean each contribute with about one half of the indirect deforestation projected for 2020 (121.970 km^2) (Lapola *et al*., 2010). Thus, indirect land use changes, especially those causing the rangeland frontier to move further into the Amazonian forests, might potentially offset carbon savings from biofuels production.

The increase in global ethanol demand, driven by global concern for addressing climate change, is leading to the development of new hydrolytic processes which aim at converting cellulose and hemicelluloses into ethanol (Santos *et al*., 2011). The expected increase in the hydrolysis technologies is *likely* to balance the requirement of land for biomass crops. Thus, the development of these technologies has a strong potential to diminish social (e.g. negative health effects due the burning process, poor labor conditions) and environmental impacts (e.g. loss of biodiversity, water and land uses) whereas at the same time it can improve the economic potential of sugarcane. One adaptation measure will be to increase the productivity of bioenergy crops due to planting in high productivity environments with highly developed technologies, in order to use less land. As one of the main centers of biotech agriculture application in the world (Gruskin, 2012), the region accounts with a great potential to achieve this goal.

As the effects previously reported on crops growing in SESA might prevail (see 27.3.4.1), i.e. that an increase in productivity may happen due to increasing precipitation, future uncertainty will have to be dealt with by preparing adapted varieties of soybean in order to maintain food and biodiesel production, mainly in Argentina as it is one of the main producers of biodiesel from soybean in the world (Chum *et al*., 2011).

Other renewable energy sources—such as wind power generation—may also be vulnerable, raising the need for further research. According to Lucena *et al*. (2009; 2010b) the projections of changes in wind power in Brazil, may not negatively influence the use of this kind of energy in the future.

Minimization of the impact of sugarcane on biodiversity and the environment is expected to improve its sustainability. As the demand for bioethanol increases, improvement of productivity will result in a greater demand of land for sugarcane production. In this context, an expansion of land under sugarcane production is *likely*, especially in Brazil's Central-South region (Lapola *et al*., 2010). However, this region also includes the cerrado (savannah) biome, which requires protection from expanding agriculture (Sawyer, 2008). It is important to ensure the protection of this unique region of Northern Brazil and Colombia as sugarcane grows into a commodity and policy is formed (Sawyer, 2008).

Initiatives such as the soy moratorium in the Amazon have an inhibitory effect over deforestation rates. Rudorff *et al*. (2011) showed that from 2008 to 2010 soybean was planted only on 0.25% of deforested land, which represents 0.027% of the total soybean cover in Brazil. Therefore, increased protection of natural areas in species-rich areas is necessary to preserve biodiversity in the face of these pressures (Brooks *et al*., 2009).

27.3.6.2. Adaptation Practices

RE will, in general, become increasingly more important over time as this is closely related with the emissions of GHG (Fischedick *et al*., 2011). Thus, RE could have an important role as adaptation means to provide sustainable energy for development in the region. However, it has to be noted that the production of RE requires large available areas for agriculture, which is the case of Argentina, Bolivia, Brazil, Chile, Colombia, Peru and Venezuela, that together represent 90% of the total area of CA and SA. However, for small countries it might not be possible to use bioenergy. Instead, they could benefit in the future from other types of RE, such as geothermal, eolic, photovoltaic etc, depending on policies and investment in different technologies. This is important because economic development is thought to be strongly correlated with an increase in energy use (Smil, 2000), which is itself associated with an increase in emissions (Sathaye *et al*., 2011).

Latin America is second to Africa in terms of technical potential for bioenergy production from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands (Chum *et al*., 2011). Some of the most important adaptation measures regarding RE are: (1) management of land use change (LUC); (2) modeling indirect land use change (ILUC); and (3) development of policies for financing and management of science and technology for all types of RE in the region.

If carefully managed, biofuel crops can be used as a means to regenerate biodiversity as proposed by Buckeridge *et al*. (2012) who pointed the fact that the technology for tropical forest regeneration has become available to the present, and that forests could share land with biofuel crops (such as sugarcane) taking advantage of forests' mitigating potential. A possible adaptation measure could be to expand the use of reforestation technology to other countries in CA and SA.

One of the main adaptation issues is the one of food *vs*. fuel, i. e. the possibility that bioenergy crops would compete for land with food crops (Valentine *et al*., 2012). This issue is important because an uncontrolled increase in bioenergy feedstocks might threaten primary food production in a scenario expected to feed future populations with an increase of 50% to 70% in production (Gruskin, 2012; Valentine *et al*., 2012). This issue is particularly important in the region as it has one of the highest percentages of arable land available for food production in the world (Nellemann *et al*., 2009). As CA and SA develop new strategies to produce more RE in the region, LUC may push ILUC so that the pressure for more acreage to produce bioenergy, for instance, might be put forward on food crops on the one hand and on biodiversity and ecosystem services on the other hand. As climate change will affect bioenergy and food crops at the same time, their effects, as well as the adaptation measures related to agriculture will be similar in both cases. The main risks identified by Arvizu *et al*. (2011) are: (1) business as usual; (2) un-reconciled growth, and (3) environment and food *vs*. fuel. Thus, the most important adaptation measures will probably be the ones related to the control of economic growth, environmental management and agriculture production. These three factors will have to be carefully managed so that their sustainability levels should be the highest possible. With this, lower emissions and consequently lower impacts of the GCC will be expected. The choice for lignocellulosic feedstocks (eg. sugarcane second generation technologies) will be quite important because these feedstocks do not compete with food (Arvizu *et al*., 2011). In the case of sugarcane, for instance, an increase

of ca. 40% in the production of bioethanol is expected as a result of the implantation of second generation technologies coupled with the first generation ones already existent in Brazil (Buckeridge *et al*., 2012; Dias *et al*., 2012).

Biodiesel production has the lowest costs in Latin America (Chum *et al*., 2011), probably due to the high production of soybean in Brazil and Argentina. The use of biodiesel to complement oil-derived diesel is a productive choice for adaptation measures regarding this bioenergy source. Also, the cost of ethanol, mainly derived from sugarcane, is the lowest in CA, SA and Latin America (Chum *et al*., 2011) and as an adaptation measure, such costs, as well as the one of bioediesel, should be lowered even more by improving technologies related to agricultural and industrial production of both. Indeed, it has been reported that in LA the use of agricultural budgets by governments for investment in public goods induces faster growth, decreasing poverty and environmental degradation (López and Galinato, 2007). One issue that may become important in the future is that the pressure of soy expansion due to biodiesel demand can lead to land use change and consequently to economic teleconnections, as suggested by Nepstad *et al*. (2006). For example, these teleconnections may link Amazon deforestation derived from soy expansion to the economic growth in China due to changes in the demand of soy. The effects of such teleconnections may possibly mean a decrease in jobs related to small to big farms in agriculture in Argentina (Tomei and Upham, 2009) on the one hand, and deforestation in the Amazon due to the advance of soybean cropping in the region on the other (Nepstad and Stickler, 2008) (see Figure 27-6).

[INSERT FIGURE 27-6 HERE
Figure 27-6: Soy teleconnections and major effects in SA. Economic growth giant consumers as China pressurize the soy production system in SA, increasing the production of biodiesel, but demanding more energy in general. (partly based on Nepstad and Stickler (2008), and Tomei and Upham (2009).]

27.3.7. Human Health

27.3.7.1. Observed and Projected Impacts and Vulnerability

Climate variability and climate change (CV/CC) are negatively affecting human health in CA and SA, either by increasing morbidity, mortality, and disabilities (very high confidence), and through the emergence of diseases in regions previously non-endemic, or the re-emergence of diseases in areas where they have previously been eradicated or controlled (high confidence) (Winchester and Szalachman, 2009; Rodríguez-Morales, 2011). Heat waves and cold spells are affecting mortality rates in cities (McMichael *et al*., 2006; Bell *et al*., 2008; Hardoy and Pandiella, 2009; Muggeo and Hajat, 2009; Hajat *et al*., 2010). Outbreaks of leptospirosis, malaria, dengue fever, and cholera were triggered in CA by hurricane Mitch in 1998 (Costello *et al*., 2009; Rodríguez-Morales *et al*., 2010). The 2010-2012 floods in Colombia (Poveda *et al*., 2011a) caused hundreds of deaths and thousands of displaced people. Dengue fever outbreaks followed floods in Brazil in the last decade (Teixeira *et al*., 2009).

Indices of malaria have increased in the last five decades, along with air temperatures, in Colombia (Poveda *et al*., 2011b; Arevalo-Herrera *et al*., 2012), as well as in urban and rural areas of Amazonia, concomitantly with large environmental changes (Gil *et al*., 2007; Tada *et al*., 2007; Cabral *et al*., 2010; Da Silva-Nunes *et al*., 2012). Malaria vector densities have increased in northwestern Argentina along with climate variables (Dantur Juri *et al*., 2010; 2011). Besides, El Niño is a major driver of malaria outbreaks in Colombia (Mantilla *et al*., 2009; Poveda *et al*., 2011b), amidst drug resistance of the parasite (Restrepo-Pineda *et al*., 2008), and human migration (Rodríguez-Morales *et al*., 2006; Osorio *et al*., 2007). Linkages between ENSO and malaria have been also reported in Ecuador and Peru (Anyamba *et al*., 2006; Kelly-Hope and Thomson, 2010), French Guiana (Hanf *et al*., 2011), Amazonia (Olson *et al*., 2009), and Venezuela (Moreno *et al*., 2007), including unheard malaria in the Andes up to 2200 m a.s.l. (Benítez and Rodríguez-Morales, 2004).

Dengue fever (DF) and dengue hemorrhagic fever (DHF) have risen in tropical America in the last 25 years, posing an annual toll of US$ 2.1+[1 to 4] billion (Torres and Castro, 2007; Tapia-Conyer *et al*., 2009; Shepard *et al*., 2011). Environmental and climatic variability affect DF and DHF incidence in Honduras and Nicaragua (Rodríguez-Morales *et al*., 2010), in Costa Rica (Fuller *et al*., 2009; Mena *et al*., 2011), in French Guiana being concurrent with

malaria (Carme *et al*., 2009; Gharbi *et al*., 2011), in cities of Colombia (Arboleda *et al*., 2009) and Venezuela. In Caracas, DF increases (decreases) during La Niña (El Niño) (Rodríguez-Morales and Herrera-Martinez, 2009; Herrera-Martinez and Rodríguez-Morales, 2010). Weather and climate variability are also associated with DF in southern SA (Honório *et al*., 2009; Costa *et al*., 2010; De Carvalho-Leandro *et al*., 2010; Degallier *et al*., 2010; Lowe *et al*., 2011). A study in Rio de Janeiro found that a 1°C (10-mm) increase in monthly minimum temperature (rainfall) led to a 45% (6%) increase in DF in the following month (Gomes *et al*., 2012). Despite large vaccination campaigns, the risk of major Yellow Fever (YF) outbreaks has increased in tropical America amidst changes in climate and environmental conditions (Jentes *et al*., 2011), mainly in densely populated poor urban settings (Gardner and Ryman, 2010).

Schistosomiasis (SCH) is an endemic Neglected Tropical Disease (NTD) in rural areas, including Brazil (Igreja, 2011), Suriname, Venezuela, and the Andean highlands, while uncontrolled peripheral urbanisation and environmental degradation increase its incidence in Brazil (Barbosa *et al*., 2010; Kelly-Hope and Thomson, 2010). It is possible that the incidence of SCH will increase as a result of increasing temperatures (Mangal *et al*., 2008; Mas-Coma *et al*., 2009; Lopes *et al*., 2010), while vegetation indices (e.g. Normalized Difference Vegetaion Index), which are directly related to climate conditions, are associated with human fascioliasis in the Andes (Fuentes, 2004).

Hantaviruses (HV) have been reported in Honduras, Panama, Costa Rica, Venezuela, Argentina, Chile, Paraguay, Bolivia, Peru, and Brazil (Jonsson *et al*., 2010; MacNeil *et al*., 2011). There is evidence that El Niño and climate change enhance the prevalence of HV (Dearing and Dizney, 2010). In Venezuela, RVs are more frequent, more severe, and more (less) common in cities with minimal (marked) seasonality (Kane *et al*., 2004). The seasonal peak of RV in Guatemala coincides with the dry season, being responsible for 60% of diarrhoea cases (Cortes *et al*., 2012).

In spite of its rapid decline, Chagas disease is still a major public health issue, in which climate and environmental changes play an important role (Abad-Franch *et al*., 2009; Araújo *et al*., 2009; Moncayo and Silveira, 2009), as in Panama and Argentina (Tourre *et al*., 2008; Gottdenker *et al*., 2011). Ciguatera fish poisoning (CFP) is a tropical disease correlated with water temperature, and thus climate change could increase its incidence across the Caribbean (Tester *et al*., 2010). Climate is an important factor of Paracoccidioidomycosis, Latin America's most prevalent mycosis (Barrozo *et al*., 2009), while ENSO is associated with recent outbreaks of bartonellosis in Peru (Payne and Fitchett, 2010).

Cutaneous leishmaniasis (CL) is correlated with climate in LA, with highest incidence in Bolivia, where it increases (decreases) during La Niña (El Niño) (Gomez *et al*., 2006; García *et al*., 2009). CL is affected in Costa Rica by temperature, forest cover, and ENSO indices (Chaves and Pascual, 2006; Chaves *et al*., 2008). Land use, altitude, and diverse climatic variables are associated with increasing trends of CL in Colombia (Valderrama-Ardila *et al*., 2010), which also increases (decreases) during El Niño (La Niña) (Cárdenas *et al*., 2006; 2007; 2008). The situation of CL in Colombia is aggravated by the internal conflict (Beyrer *et al*., 2007). In Venezuela, CL increased (67%) during a weak La Niña (Cabaniel *et al*., 2005). CL is a seasonal disease in Suriname peaking during the March dry season (35%) (Van der Meide *et al*., 2008), while in French Guiana it is intensified after the October-December dry season (Rotureau *et al*., 2007). The incidence rates of visceral leishmaniasis (VL) have been increasing in Brazil (the highest in LA) owing to deforestation (Cascio *et al*., 2011; Sortino-Rachou *et al*., 2011), and to the occurrence of El Niño (Ready, 2008), as is also the case in Argentina, Paraguay, and Uruguay (Bern *et al*., 2008; Dupnik *et al*., 2011; Salomón *et al*., 2011; Fernández *et al*., 2012). VL transmission in western Venezuela is also associated with the bimodal annual rainfall regime (Feliciangeli *et al*., 2006; Rodríguez-Morales *et al*., 2007). On the other hand, the incidence of skin cancer in Chile has increased in recent years, which is statistically correlated to climatic and geographic variables (Salinas *et al*., 2006).

Onchocerciasis (river blindness) is another climate-related disease (Botto *et al*., 2005), whose vector exhibits clear-cut wet-dry seasonal biting rates (Rodríguez-Pérez *et al*., 2011). Leptospirosis is particularly prevalent in warm and humid tropical regions of CA (Valverde *et al*., 2008). Other climate-driven infectious diseases are ascariasis and gram-positive cocci in Venezuela (Benítez *et al*., 2004; Rodríguez-Morales *et al*., 2010), and Carrion's disease in Peru (Huarcaya *et al*., 2004)

Sea water temperature affects the abundance of the bacteria responsible for cholera (Koelle, 2009; Jutla *et al*., 2010; Marcheggiani *et al*., 2010; Hofstra, 2011), and thus high correlations exist between El Niño and cholera in Peru, Ecuador, Colombia, Mexico and Venezuela (Cerda Lorca *et al*., 2008; Martínez-Urtaza *et al*., 2008; Salazar-Lindo *et al*., 2008; Holmner *et al*., 2010; Gavilán and Martínez-Urtaza, 2011; Murugaiah, 2011). Extreme temperatures and changes in rainfall may also increase food safety hazards along the food chain (Sivakumar *et al*., 2005; Tirado *et al*., 2010).

Air pollution and higher temperatures exacerbate chronic respiratory and cardiovascular problems. Dehydration from heatwaves increases hospitalizations for chronic kidney diseases (Kjellstrom *et al*., 2010), mainly affecting construction workers, and CA sugarcane and cotton workers (Crowe *et al*., 2009; 2010; Kjellstrom and Crowe, 2011; Peraza *et al*., 2012). In the region, atmospheric pollutants are associated with artherosclerosis, respiratory and cardiovascular diseases, pregnancy-related outcomes, cancer, cognitive deficit, otitis, and diabetes (Olmo *et al*., 2011). The worsening of air quality in large cities is increasing allergic respiratory diseases, and morbidity from asthma and rhinitis (Grass and Cane, 2008; Martins and Andrade, 2008; Gurjar *et al*., 2010; Jasinski *et al*., 2011; Rodriguez *et al*., 2011).

Extreme weather and climate events affect mental health by exposure to psychological trauma (Higginbotham *et al*., 2006; Berry *et al*., 2010). Drought-prone areas in NEB are vulnerable to lower socioeconomic and educational levels, in turn associated with depression, psychological distress, and anxiety (Coêlho *et al*., 2004). Hospital admissions for mania and bipolar disorder are associated with climate seasonality in Brazil. Extreme weather, meager crop yields, and low GDP are also linked with increased violence (McMichael *et al*., 2006). All these problems may be exacerbated by climate change (Schulte and Chun, 2009).

Many factors increase CA and SA's vulnerability to climate change: precarious health systems, socio-economic factors, inadequate water and sanitation services, poor waste collection and treatment systems, air, soil and water pollution, lack of social participation, and inadequate governance (Luber and Prudent, 2009; Rodríguez-Morales, 2011; Sverdlik, 2011). Human health vulnerabilities exhibit serious biases with geography, age (Perera, 2008; Martiello and Giacchi, 2010; Graham *et al*., 2011; Åstrom *et al*., 2011), gender (Oliveira *et al*., 2011), race, ethnicity, and socio-economic status (Diez Roux *et al*., 2007; Martiello and Giacchi, 2010). Malnutrition due to crop failure and drought adds up to vulnerability (Schmidhuber and Tubiello, 2007). NTDs cause 1.5-5.0 million disability-adjusted life years (DALYs- a measure of disease burden, expressed as the number of years lost owing to disability, ill-health or early death) in LA, many of which are climate-sensitive diseases (Hotez *et al*., 2008; Allotey *et al*., 2010). Mega-cities' vulnerability (see 27.3.5) is aggravated by the provision of drinking water and by the rapid spread of diseases. It further is increasing due to migration from rural areas forced by environmental degradation and disasters (Campbell-Lendrum and Corvalán, 2007; Borsdorf and Coy, 2009; Hardoy and Pandiella, 2009), and in turn mega-cities are vulnerable to natural disasters (earthquakes, fires, storms etc.) that might change in frequency and intensity in the context of global climate change. The provision of drinking water and the spread of diseases make mega-cities vulnerable to global environmental change (Borsdorf and Coy, 2009). Diverse vulnerability assessments to the impacts of climate change on human health have been developed in Brazil at national, regional and municipal scales. The approach uses composite indicators, which included downscaled climate scenarios, epidemiological variables, economic and demographic projections and the status of natural ecosystems (Confalonieri *et al*., 2009; 2011; Barbieri and Confalonieri, 2011; FIOCRUZ, 2011). The Andes and CA are among the regions of highest predicted losses [1% to 27%] in labor productivity from future climate scenarios (Kjellstrom *et al*., 2009). Argentina and Chile (under the sub-Antarctic atmospheric circulation) might suffer serious health effects from impacts to water and food availability, and extreme weather (Team and Manderson, 2011).

27.3.7.2. Adaptation Strategies and Practices

Despite the attempt to implement adaptation strategies in CA and SA ((Blashki *et al*., 2007; Costello *et al*., 2011), several factors hamper their effectiveness, such as: a lack of political commitment, gaps in scientific knowledge, and institutional weaknesses of health systems (Keim, 2008; Lesnikowski *et al*., 2011; Olmo *et al*., 2011) (see section 27.4.3)

Research priorities and current strategies must be reviewed to achieve better disease control (Halsnæs and Verhagen, 2007; Romero and Boelaert, 2010; Karanja *et al*., 2011). The low adaptive capacity of rural communities associated with poor health systems and limited resources exacerbate human health stressors from climate change, and thus regional responsive systems must be put in place in key operational areas (Bell, 2011), involving adaptive capacity building, and implementation of adaptation actions (Huang *et al*., 2011), which in turn require considering the potential magnitude and uncertainty of the hazards, and the effectiveness, costs, and risks of the proposed responses (Campbell-Lendrum and Bertollini, 2010).

Diverse human wellbeing indices must be explicitly stated as climate change policies of adaptation and mitigation in LA, along with the Millennium Development Goals (Franco-Paredes *et al*., 2007; Halsnæs and Verhagen, 2007; Mitra and Rodriguez-Fernandez, 2010). South-south cooperation and multidisciplinary research is required to study the health impacts of climate change and to identify resilience, adaptation, and mitigation strategies (Tirado *et al*., 2010; Team and Manderson, 2011). Colombia is starting to develop a pilot human health adaptation program, to cope with climate-driven changes in malaria transmission and exposure (Poveda *et al*., 2011b). The city of São Paulo has implemented diverse local pollution control measures, with the co-benefit of reducing GHG emissions, such as the 11% reduction of methane by landfills (De Oliveira, 2009; Nath and Behera, 2011).

27.4. Adaptation Opportunities, Constraints, and Limits

27.4.1. Adaptation Needs and Gaps

During the last years, the study of adaptation to climate change has progressively switched from an impact-focused approach (mainly climate-driven) to a vulnerability-focused vision (Boulanger *et al*., 2011). While different frameworks and definitions of vulnerability exist, a general tendency aims at studying vulnerability to climate change especially in SA and CA using a holistic or systemic approach (Ison, 2010; Carey *et al*., 2012b), where climate drivers are actually few with respect to all other drivers related to human and environment interactions including physical, economic, political and social context, as well as local characteristics such as occupations, resource uses, accessibility to water, etc. (Manuel-Navarrete *et al*., 2007; Young *et al*., 2010).

In developing and emergent countries, there exists a general consensus that the adaptive capacity is low, strengthened by the fact that poverty is a limit to resilience (Pettengell, 2010) leading to a “low human development trap” (UNDP, 2007). Although this is true, Magnan (2009) suggests that this analysis is biased by a “relative immaturity of the science of adaptation to explain what are the processes and the determinants of adaptive capacity”. Increasing research efforts on the study of adaptation is therefore of great importance to improve our understanding of the actual societal, economical, community and individual drivers defining the adaptive capacity. Especially, a major focus on traditions and their transmission (Young and Lipton, 2006) may actually indicate potential adaption potentials in remote and economically poor regions of SA and CA. Such a potential does not dismiss the fact that the nature of future challenges may actually not be compared to past climate variability (e.g. glacier retreat in the Andes).

Coping with new situations may require new approaches such as a multilevel risk governance (Young and Lipton, 2006; Corfee-Morlot *et al*., 2011) somehow associated with decentralization in decision-taking and responsibility. While the multilevel risk governance and the local participatory approach are interesting frameworks for strengthening adaptation capacity, their major counterpart is that at all levels it requires (from local to national levels) capacity-building and information transmission on future risks, major challenges and possible methodologies to plan adaptation strategies to climate change. At present, despite an important improvement during the last years, there still exists a certain lack of awareness of environmental changes and mainly their implications for livelihoods and businesses (Young *et al*., 2010). Moreover, considering the limited financial resources of some states in CA and SA, long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the population. This situation weakens the importance of adaptation planning to climate change in the political agenda, and requires therefore international involvement as one facilitating factor in natural hazard management and climate change adaptation (Carey *et al*., 2012b). However, as pointed out by McGray *et al*. (2007), development, adaptation and mitigation issues are not separate issues. Especially,

development and adaptation strategies should be tackled together in developing countries sch as SA and CA, focusing on strategies to reduce vulnerability. The poor level of adaptation of present-day climate in SA and CA countries is characterized by the fact that responses to disasters are mainly reactive rather than preventive. Some early warning systems are being implemented, but the capacity of responding to a warning is often limited, particularly among poor populations. Finally, actions combining public communication (and education), public decision-maker capacity-building and a synergetic development-adaptation funding will be key to sustain the adaptation process that CA and SA require to face future climate change challenges.

27.4.2. Practical Experiences of Adaptation, including Lessons Learned

Adaptation processes have been in many cases initiated a few years ago, and there is still a lack of literature to evaluate their efficiency in reducing vulnerability and building resilience of the society against climate changes. However, some lessons have already been learned on these first experiences (see section 27.3). In CA and SA, many societal issues are strongly connected to development goals and are often considered priority in comparison to adaptation efforts to climate change. However, according to the 135 case studies analyzed by McGray *et al.* (2007), 21 of which were in CA and SA, the synergy between development and adaptation actions allows to ensuring a sustainable result of the development projects.

Vulnerability and disaster risk reduction may not always lead to long-term adaptive capacity (Tompkins *et al.*, 2008; Nelson and Finan, 2009), except when structural reforms based on good governance (Tompkins *et al.*, 2008) and negotiations (Souza Filho and Brown, 2009) are implemented. While multi-level governance can help to create resilience and reduce vulnerability (Roncoli, 2006; Young and Lipton, 2006; Corfee-Morlot *et al.*, 2011), capacity-building (Eakin and Lemos, 2006), good governance and enforcement (Lemos *et al.*, 2010; Pittock, 2011) are key components.

Local adaptation to climate and non-climate drivers may undermine long-term resilience of social-ecological systems when local, short-term strategies designed to deal with specific threats or challenges do not integrate a more holistic and long-term vision of the system at threat (Adger *et al.*, 2011). Thus, policy should identify the sources of and conditions for local resilience and strengthen their capacities to adapt and learn (Adger *et al.*, 2011; Eakin *et al.*, 2011), as well as to integrate new adapted tools (Oft, 2010). This sets the question of convergence between the local-scale/short-term and broad scale/long-term visions in terms of perceptions of risks, needs to adapt and appropriate policies to be implemented (Eakin and Wehbe, 2009; Salzmann *et al.*, 2009). Even if funding for adaptation is available, the overarching problem is the lack of capacity and/or willingness to address the risks, especially those threatening lower income groups (Satterthwaite, 2011). Adaptation to climate change cannot eliminate the extreme weather risks, and thus efforts should focus on disaster preparedness and post-disaster response (Sverdlik, 2011). Migration is the last resort for rural comunities facing water stress problems in CA and SA (Acosta-Michlik *et al.*, 2008).

In natural hazard management contributing to climate change adaptation, specific cases such as the one in Lake 513 in Peru (Carey *et al.*, 2012b) clearly allowed to identify facilitating factors for a successful adptation process (technical capacity, disaster events with visible hazards, institutional support, committed individuals, and international involvement) as well as impediments divergent risk perceptions, imposed government policies, institutional instability, knowledge disparities, and invisible hazards).

In certain cases, forward-looking learning (anticipatory process), as a contrast to learning by shock (reactive process), has been found as a key element for adaptation and resilience (Tschakert and Dietrich, 2010) and should be promoted as a tool for capacity-building at all levels (stakeholders, local and national governments). Its combination with role-playing game and agent-based models (Rebaudo *et al.*, 2011) can strengthen and accelerate the learning process.

27.4.3. Observed and Expected Barriers to Adaptation

It is usually considered that a major barrier to adaptation is the perception of risks and many studies focused on such an issue (Bonatti *et al*., 2012). However, new studies (Adger *et al*., 2009) identified social limits to possible adaptation to climate change in relation with issues of values and ethics, risk, knowledge and culture, even though such limits can evolve in time. Indeed, while being a necessary condition, perception may not be the main driver for initiating an adaptation process. As pointed out by Tucker et al. (2010), exogenous factors (economic, land tenure, cost, etc.) may actually strongly constrain the decision-making process involved in possible adaptation process.

Moreover, it is difficult to describe adaptation without defining at which level it is thought. Indeed, while a lot of efforts are invested in national and regional policy initiatives, most of the final adaptation efforts will be local. National and international (transborder) governance is key to build adaptive capacity (Engle and Lemos, 2010) and therefore to strengthen (or weaken) local adaptation through efficient policies and delivery of resources. At a smaller scale (Agrawal, 2008), local institutions can strongly contribute to vulnerability reduction and adaptation. However, at all levels, the efficiency in national and local adaptation activities strongly depend on the capacity-building and information transmission to decision-makers (Eakin and Lemos, 2006).

27.4.4. Planned and Autonomous Adaptation

Autonomous adaptation strategies are mainly realized at local levels (individual or communitarian), but not always respond to climate forcing. For instance, the agricultural sector adapts rapidly to economic stressors, while, despite a clear perception of climate risks, it may last longer before responding to climate changes (Tucker *et al*., 2010). In certain regions or communities, such as Anchioreta in Brazil (Bonatti *et al*., 2012), adaptation is part of a permanent process and is actually tackled through a clear objective of vulnerability reduction, maintaining and diversifying a large set of natural varieties of corn allowing the farmers to diversify their planting. Another kind of autonomous adaptation is the southward displacement of agriculture activities (e.g. wine, coffee) though the purchase of lands, which will become favorable for such agriculture activities in a warmer climate. In Argentina, the increase of precipitacion observed during the last 30 years contributed to a westward displacement of the crop frontier.

Planned adaptation is by definition associated to government policies and planning. During the last years, there has been a growing awareness of CA and SA governments on the need to integrate climate change and future climate risks in their policies. Up to date, in total 18 regional Non-Annex countries, including Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Guyana, Panama, Paraguay, Peru, Suriname, Uruguay and Venezuela, have already responded through their initial and most cases second National Communication to the UNFCCC from 1997 until 2012 (see UNFCCC, 2012) allowing to measure the country's emissions and to assess its present and future vulnerability. In addition, for instance Argentina, Brazil and Uruguay among others, created specific Secretaries in the government organizations specifically dedicated to climate change in order to coordinate actions between different ministries and secretaries of state. Finally, most of the countries in the region (Keller *et al*., 2011) are now involved in international networks focused on adaptation to climate change, or in international projects aiming at capacity-building and design of adaptation strategies. As an example, the 'CentroAmerican Integration System' (see SICA, 2013 gathers every three months climate experts for regional institutions as well as sectorial experts (agriculture, energy, etc.) in order to discuss climate trends, increase capacity-building and anticipate major climate threats. It is of course too early to evaluate the actual impact of such new initiatives on regional or national adaptation to climate change. However, new tools (Debels *et al*., 2009) or international platforms for CA and SA may help to prioritize adaptation policies according to their efficiency and the limited financial resources in the future (Kok *et al*., 2007).

Table 27-7 presents programs, projects and initiatives with focus on current and past practical adaptation measures maintained in the data collection by the UNFCCC under the Nairobi Work Programme (NWP) (distinguishing Private Sector Initiatives (PSI); Local Coping Strategies (LCP) (UNFCCC, 2012b); EbA approaches; and Adaptation Practices (AP); complemented with international projects from the weAdapt database (weAdapt, 2012).

[INSERT TABLE 27-7 HERE
Table 27-7: Overview on local, regional, national and international adaptation programs, projects and initiatives relevant for the region]

27.5. Interactions between Adaptation and Mitigation

As demonstrated in 'The SouthSouthNorth Capacity Building Module on Poverty Reduction" (see SSN, 2006), a synergy between adaptation and mitigation strategies can be reached especially when the community organizes itself in a cooperative. In many examples, mitigation strategies based on a cooperative system, which manages recycling or renewable energy production, actually lead to an increase in energy availability, crucial to increase production capacity and thus to create new financial resources for the community. As also pointed out by (Venema and Cisse, 2004), the growth of renewable energy in CA and SA (see also section 27.3.6) should not be limited to large infrastructure projects, and should also encompass the development of decentralized renewable energy solutions. In spite of their smaller size (individual or communitarian), these solutions offer adaptation and mitigation benefits. On one hand, fossil-based energy consumption is reduced, while energy availability is increased. On the other hand, reduction of energy precariousness is key in any development strategy. Thus, it allows local community and individuals to growing socially and economically; and therefore to reducing its vulnerability avoiding the poverty trap (UNDP, 2007), and to initiating an adaptation process based on non-fossil fuel energy sources. Such initiatives also depend on local and organizational leaderships (UN-Habitat, 2011).

At national and regional scales, CA and SA countries will require the allocation of human and financial resources to adapt to climate change. While resources are limited, too large an economic dependence of these countries to fossil fuels will reduce their adaptive capacity. The reduction in energy consumption and the integration of renewable energies in their energetic matrix is therefore a key issue for all these countries in order to sustain their development and growth and therefore increase their adaptive capacity (see also section 27.3.6).

27.6. Case Studies

27.6.1. Hydropower

Hydropower is the main source of renewable energy in CA and SA (see section 27.3.6). Although there is debate about GHG emissions from hydropower reservoirs (especially in tropical environments, Fearnside and Pueyo, 2012) this form of electricity generation is often seen as a major contributor to mitigating GHG emissions worldwide (see IPCC SRREN [5]; Kumar *et al*. (2011). On the other hand, hydropower is also a climate-related (water) sector, thus making it prone to serious efects from climate change (see section 27.3.1.1).

The CA and SA region constitute a unique example to study these relations between climate change mitigation and adaptation in relation to hydropower generation. According to the Special Report on Renewable Energy Sources and Climate Change Mitigation (see Table 5.1 SRREN; IPCC, 2011) CA and SA are second to Asia in terms of hydropower energy generation in the world, displaying a 20% share of total annual generation. The quality of water resources availability in CA and SA is the largest in the world with an average regional capacity factor of over 50%. As a result, the region has by far the largest proportion of electricity generated through hydropower facilities (Table 27-6 in section 27.3.6.1). The hydropower proportion of total electricity production is over 40% in the region, and in some cases is near or close to 80%, as in the case of Brazil, Colombia and Costa Rica.

Diverse studies have analyzed the potential impacts of climate change on hydropower generation (see details in Table 27-4 in section 27.3.1.1). Maurer *et al*. (2009) studied future hydrologic conditions for the Lempa River basin across El Salvador, Honduras and Guatemala, which feeds major hydroelectric facilities. Assesmment of projections including uncertainty analysis show a reduction in hydropower capacity of 33% to 53% by 2070-2099. A similar loss is expected for the Sinu-Caribe basin in Colombia were, despite a general projection of increased precipitation, losses due to evaporation enhancement reduces inflows to hydroelectric systems, thus reducing electricity generation up to 35% compared to base conditions (Ospina-Noreña *et al*., 2009a). Further studies (Ospina-Noreña *et al*., 2011a;

2011b) have estimated vulnerability indices for the hydropower sector in the same basin, and identified reservoir operation strategies to reduce this vulnerability. Overall reductions in hydropower generation capacity are also expected in Chile for the main hydropower generation river basins: Maule, Laja and Biobio (ECLAC, 2009a; McPhee *et al*., 2010; Stehr *et al*., 2010), and also in the Argentinean Limay River basin (Seoane and López, 2007). Ecuador, on the other hand, faces an increase in generation capacity associated with an increment in precipitation on its largest hydroelectric generation Paute River basin (Buytaert *et al*., 2010). In Brazil, the country with the largest installed hydroelectric capacity in the region, continuous efforts are made to improve the management of the system under variable climatic conditions (Lima and Lall, 2010). There is still unused generation capacity in sub-basins of the Amazon River (Soito and Freitas, 2011), but future climate conditions plus environmental concerns pose an important challenge for the expansion of the system (Freitas and Soito, 2009; Finer and Jenkins, 2012). According to Lucena *et al*. (2009), hydropower systems in southern Brazil (most significantly the Parana River system) could face a slight increase in energy production under an A2 scenario. However, the rest of the country's hydropower system, and especially those located in the North East region, could face a reduction in power generation, thus reducing the reliability of the whole system (Lucena *et al*., 2009).

An obvious implication of the mentioned impacts is the need to replace the energy lost due to climate change impacts. In this regard, a typical adaptation measure would be to increase alterantive energies (see 27.3.6.2). Lower cost of adaptation measures have been studied for Brazil (Lucena *et al*., 2010a), with results implying an increase in natural gas and sugarcane bagasse electricity generation in the order of 300 TWh, increase in operation costs in the order of 7 billion USD annually and 50 billion USD in terms of investment costs by 2035. In the case of Chile, ECLAC (2009a) assumed that the loss in hydropower generation would be compensated by the least operating cost source available (not used probably at full capacity), which is a coal-fired power plant. In this case, the amount of average electricity that needs to be replaced for the 2011-2040 period is around 18 TWh of electricity, a little over 10% of actual total hydropower generation capacity in the country (ECLAC, 2009a). According to the same study (ECLAC, 2009a), this implies an increase in operating costs of the order of 100 million USD annually and an increase of 2 $MTCO_2e$ (total emissions from the electricity generation subsector in Chile are around 25 $MTCO_2e$ in 2009). Ospina-Noreña (2011a; 2011b) studied some adaptation options, such as changes in water use efficiency or demand growth that could mitigate the expected impacts on hydropower systems in the Colombian Sinú-Caribe River basin.

Some other implications are, for instance, changes in the seasonality of inflows to hydropower generation systems such as those projected for Peru (Juen *et al*., 2007), Chile (ECLAC, 2009a), and Argentina (Seoane and López, 2007), that could affect the relationship between different water users within a basin. In Chile for example, hydrologic impacts of climate change could affect water supply to agriculture irrigation triggering economic and social conflicts between this and the hydropower sector that share water resources from the same river basin. It is worth noting that those regions which are projected to face an increase in streamflow and associated generation capacity, such as Ecuador or Costa Rica, also share difficulties in managing deforestation, erosion and sedimentation which limits the useful life of reservoirs (see section 27.3.1.1). In these cases it is important to consider these effects in future infrastructure operation (Ferreira and Teegavarapu, 2012) and planning, and also enhance the on-going process of recognizing the value of the relation between ecosystem services and hydropower system operations (Leguía *et al*., 2008) (see more on PES in section 27.3.2.2).

27.6.2. Payment for Ecosystem Services

Payment for ecosystem services (PES) is commonly described as a set of transparent schemes for securing a well-defined ecosystem service (or a land use capable to secure that service) through conditional payments or compensations to voluntary providers (Engel *et al*., 2008; Tacconi, 2012). Van Noordwijk *et al*. (2012) provides a broader definition to PES by arguing that it encompasses three complementary approaches, (i) the one above, i.e., commodification of pre-defined ecosystem services so that prices can be negotiated between buyers and sellers; plus (ii) compensation for opportunities forgone voluntarily or by command and control decisions; and (iii) coinvestment in environmental stewardships. Therefore, the terms ´conservation agreements´, ´conservation incentives´ and ´community conservation´ are often used as synonyms or as something different or broader than PES (Milne and

Niesten, 2009; Cranford and Mourato, 2011). For simplicity, we refer to PES in its broadest sense (sensu van Noordwijk *et al*., 2012).

Services subjected to such types of agreements often include regulation of freshwater flows, carbon storage, provision of habitat for biodiversity, and scenic beauty (De Koning *et al*., 2011; Montagnini and Finney, 2011). Since the ecosystems that provide the services are mostly privately owned, policies often aim at supporting landowners to maintain the provision of services over time (Kemkes *et al*., 2010). Irrespective of the debate of as to whether payments or compensations should be designed to focus on actions or results (Gibbons *et al*., 2011), experiences in Colombia, Costa Rica and Nicaragua show that PES can finance conservation, ecosystem restoration, and better land use practices (Montagnini and Finney, 2011; see also Table 27-5). However, based on examples from Ecuador and Guatemala, Southgate *et al*. (2010) argue that uniformity of payment for beneficiaries can be inefficient if recipients accept less compensation in return for conservation measures, or if recipients that promote greater environmental gains receive only the prevailing payment. Other setbacks to PES schemes might include cases where there is a perception of commoditization of nature and its intangible values (e.g. Bolivia, Cuba, Ecuador and Venezuela), cases where mechanisms are inefficient to reduce poverty, slowness to build trust between buyers and sellers, as well as gender and land tenure issues that might arise (Asquith *et al*., 2008; Peterson *et al*., 2010; Balvanera *et al*., 2012; van Noordwijk *et al*., 2012).

Table 27-8 lists selected examples of PES schemes in Latin America, but a more complete and detailed list is given in Balvanera *et al*. (2012).

[INSERT TABLE 27-8 HERE
Table 27-8: Cases of government-funded PES schemes in CA and SA.]

The PES concept (or ´fishing agreements´) also applies to coastal and marine areas, although only a few cases have been reported. Begossi (2011) argues that this is due to three factors: origin (the mechanism was originally designed for forests), monitoring (marine resources such as fish are more difficult to monitor than terrestrial resources) and definition of resource boundaries in offshore water. One example of a compensation mechanism in the region is the so-called *defeso*, in Brazil. It consists of a period (reproductive season) when fishing is forbidden by the government and fishermen receive a financial compensation. It applies to shrimp, lobster and both marine and freshwater fisheries (Begossi *et al*., 2011).

27.7. Data and Research Gaps

The lack of high quality and continuous climate, oceanic and hydrological records, together with the very few complete regional studies, poses challenges for the region to address climate variability and the identification of trends in climatic extremes, in particular for CA. The non-availability of high resolution climatic and hydrological data also hampers studies on frequency and variability of extremes. This situation affects the studies of related impacts and vulnerability analyses in present climates, and the development of vulnerability assessments and adaptation actions for the future.

Related with observed impacts in most of the sectors, there is a great difference in information availability between countries, While more studies have been performed for the SESA region, much less are available for CA and for some regions of tropical SA. The problem is not only the lack of studies of observed impacts, but also the lack or poor dissemination of results in peer-reviewed publications. There is a need for studies focused on current impacts and vulnerabilities in all the sectors throughout CA and SA, potentially with a certain emphasis on extremes in order to improve risk management assessments.

The complex interactions between climate and non-climate drivers can challenge impacts assessment and projections, as can for instance be the case for water availability and streamflow when looking at current and potential deforestation; or overfishing and pollution regarding the impacts on fisheries, or impacts on hydroenergy production. In this sense, the lack of interdisciplinary integrated studies limits the knowledge of such complex processes that involve not only physical but also socioeconomical factors.

In addition, the accelerated changes in some issues like deforestation and changes in land use, as well as economic conditions, demand continuous and detailed studies to update available information to be made available to the research community.

To address the global challenge of food secturity and food quality, being important issues in CA and SA, investments in the production of scientific agricultural knowledge will be reinforced in relation to: integration of agriculture with organic production; and the integration of food and bioenergy production. With the important interlinakges of renewable energy, adaptation and mitigation, sufficient knowledge on RE project implementation and on crops is requested.

Also, a better understanding is needed of potential adverse effects of bioenergy production and indirect land use changes. Equally, further research is needed on future projections of renewable energy, e.g. wind power. However, it is indispensable that the competition for food and bioenergy production considers ethical aspects; identifying which activity is most important and whether bioenergy production would affect food security.

Sea level rise and costal erosion are also relevant issues, and the lack of comparable measurements of sea level rise in CA and SA makes integrated assessments on sea level rise and impacts on the region difficult, both for the present and future. Of local and global importance will be an enhancement of the understanding of the physical processes on the ocean, in specific the Humboldt Current system flowing along the West Coast of SA, being the most fish productive system worldwide.

While the majority of the coastal section literature focuses on fisheries, there is a recognized need for research on how corals reefs, mangroves and benthic marine invertebrates, that are key to reef systems as well, could be impacted upon by climate change.

There is still a need for more research and information about the impacts of climate variability and change on human health, mainly in CA. One problem is the difficulty to accessing health data that are not always archived and ready to be used in integrated studies. Another need refers to building the necessary critical mass of transdisciplinary scientists to tackle the climate change-human health problems in the region. The prevailing gaps in scientific knowledge hamper the implementation of adaptation strategies, thus demanding a review of of research priorities towards better disease control. With the aim of further studying the health impacts of climate change and identifying resilience, mitigation and adaptation strategies, South-South cooperation and multidisciplinary research are considered to be relevant priorities.

In despite of the uncertainty that stems from global and regional climatic projections, the region needs to act. In this sense it is usseful to promote research activities leading to assist people to cope with current climate variability, as for example, risk assessment and risk management. Other important aspect is the improvement of climate modeling that can be done in the region, thus lowering uncertaintities. Since the AR4, experiences on model development and the generation of high resolution climate scenarios have allowed for the production of the first integrated regional studies on impacts and vulnerability assessments of climate change, for sectors such as agriculture, energy and human health.

Research on adaptation and the scientific understanding of the various processes and determinants of adaptive capacity is also key to the region, with particular potential in increasing adaptation capacity when focusing on traditions and how they are transmitted. Linking indigenous knowledge with scientific knowledge is also needed. Although adaptation processes have mostly been intiated in the past years, still their efficiency is difficult to determine owing to a lack of literature to evaluate them.

There is a need for change in the research agenda in order to address vulnerability and foster adaptation in the region; encompassing an inclusion of the regions' researchers and focusing also on governance structures and action-oriented research that also addresses resource distribution inequities.

Regional and international partnerships, networks, research programs have allowed a linkage of those programs with local strategies for adaptation and mitigation, also providing opportunities to address research gaps and exchange among researchers. Examples are the Ibero-American Network of Climate Change Offices- RIOCC; the European Union funded projects CLARIS LPB in SESA and AMAZALERT in Amazonia. Other important initiaves come from the WHO, GEF, IDB, ECLAC (CEPAL), La Red, BirdLife International. The same holds for local international networks such as ICLEI or C40, of which CA and SA cities form part. The weADAPT initiative is a good example on how practitioners, researchers and policy makers for CA and SA can have access to credible, high quality information and to share experiences and lessons learnt in other regions of the world.

27.8. Conclusions

In CA and SA there is ample evidence of increases in extreme climate events and on their impacts on natural and human systems. Changes in climate variability and in extreme events have been severely affecting CA and SA since the second half of the 21st century. Since the AR4, unusual extreme weather and climate events have occurred in most countries: drought/flood episodes in Amazonia in 2010/2009, 2012, the drought in NE Brazil in 2012, cold waves and floods in the Andes from 2010-2012, among others. Temperature increases have been identified in most of CA and SA, with the exception of the southern coast of South America that has experienced cooling during the last decades. Changes in observed warm days and cold nights have been identified in CA, and some sectors of SA, while more frequent and intense rainfall extremes in SESA have favored an increase in the occurrence of landslides and flash floods. Since the AR4, there is growing evidence that glaciers (both tropical and extratropical) are retreating and the cryosphere in the Andes is changing according to the warming trends, affecting the hydrometeorological regimes in SA.

Land cover change is a key driver of environmental change with significant impacts on climate change. Deforestation and land degradation are mainly attributed to increased extensive and intensive agriculture, both from traditional export activities such as beef and soy production, but more recently from biomass for biofuel production. Even though deforestation rates in the Amazon have decreased substantially in the last eight years, other regions like the Cerrado and the Chaco forests still present high levels of deforestation with rates as high as 1.33%. In Argentina, Bolivia, Brazil and Paraguay, agricultural expansion, mainly soybean, has exacerbated deforestation and has intensified the process of land degradation. The agricultural expansion has affected fragile ecosystems such as the edges of the Amazon forest and the Pampas region; or the tropical Andes, increasing the vulnerability of communities to extreme climate events, particularly floods, landslides and droughts.

Socioeconomic development shows a high level of structural heterogeneity and a very unequal income distribution resulting in the high vulnerability of the region to climate variability and change. There is still a high and persistent level of poverty in most countries in spite of the sustained economic growth observed in the last decade. The economic inequality translates into inequality in access to water, sanitation and adequate housing; particularly for the most vulnerable groups living in poverty. However, high vulnerability can be found in regions with high income.

Coastal and marine ecosystems have been undergoing significant transformations that pose threats to marine excosystems and to the services they offer. Frequent coral bleaching events have been recently reported for the Mesoamerican Coral Reef. In CA and SA, some of the main drivers of mangrove loss are deforestation and land conversion, agriculture and shrimp ponds, to an extent that the mangroves of the Atlantic and Pacific coasts of CA are some of the most endangered in the planet. Changes over 2 mm/yr of sea-level rise have been found in CA and SA, which is reason for concern since 3/4 of the population of the region live within the range of 200 km of the coast.

Conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss in the region, and in parallel is a driver of anthropogenic climate change. Plant species are rapidly declining in CA and SA; the highest percentage of rapidly declining amphibian species occurs also in CA and SA; with Brazil being among the countries with most threatened bird, mammal species and freshwater fish. However, the region has still large extensions of natural vegetation cover for which the Amazon is the main example. Ecosystem-based Adaptation practices, such as

conservation agreements, community management of natural areas, and payment for ecosystem services, begin to appear across the region.

Figure 27-7 presents a summary of some of the main observed trends in global environmental change drivers across different representative regions of CA and SA. The figure presents changes in climate and non climate drivers and has to be compounded with other socioeconomic related trends, such as the rapid urbanization process experienced the region.

[INSERT FIGURE 27-7 HERE
Figure 27-7: Summary of observed changes in climate and other environmental factors in representative regions of CA and SA. The boundaries of the regions in the map are conceptual (not precise geographic nor political) and follow those developed in Figure 3-1 of the IPCC SREX (IPCC, 2012). Information and references to changes provided are presented in different sections of the chapter.]

In terms of attribution to climate change, some of the observed impacts on human and natural systems detected and reported in the literature are shown in Figure 27-8. Some of them can be directly or indirectly attributed to human influences, and can be summarized as:

- Reduction in tropical glaciers and icefields in tropical and extra tropical Andes over the second half of the 20th century that can be attributed to an increase in temperature.
- There have changes identified in river flows in SA. Extreme streamflow in the Amazon River have changed during the last two decades, robust positive trends in streamflow in different sites have been detected in sub-basins of the La Plata River basin and increased dryness for most of the river basins in west coast of South America have been detected during the last 50 years.
- Mangrove degradation in the Northern South American coast and reduction in fisheries stock.
- Increase in agricultural yield in SESA, and shifting in agricultural zoning: significant expansion of agricultural areas, mainly in climatically marginal regions.
- Increase in frequency and extension of dengue fever, yellow fever and malaria.

However, the fact that in some impacts the number of studies is still insufficient leads to extreme low levels of confidence for attribution to human influences.

[INSERT FIGURE 27-8 HERE
Figure 27-8: Observed impacts of climate variations and attribution of causes in CA and SA.]

By the end of the century, the projected mean warming for CA ranges from 1.5°C to 4.0 °C, while rainfall tends to decrease between 5 and 10%. SA shows a warming between 1.0°C to 5.0 °C, with rainfall reduction up to 10% in tropical SA and an increase of about 10-15% in SESA, and in other regions of the continent. Heavy precipitation is projected to increase in SESA, while dry spells would increase in northeastern South America. Increases in warm days and nights are very likely to occur in most of SA. Projections for CA show summertime precipitation reduction, accompanied by projected warming in most of the region. However, there is some degree of uncertainty on climate change projections for regions, particularly for rainfall.

In present climates, there are regions that experience vulnerability in terms of current water availability, and this vulnerability is expected to increase in the future due to climate change impacts. Already vulnerable regions in terms of water supply, like the semi-arid zones in SA and CA and the tropical Andes, are expected to increase even further their vulnerability due to climate change. This would be complicated by the expected glacier retreat, and a reduction in water availability due to expected precipitation reduction and increase evapotranspiration demands as expected in the semi-arid regions of CA and SA. These scenarios would affect water supply for large cities, small communities, hydropower generation and the agriculture sector.

This results in a need for re-assessing current practices to reduce the mismatch between water supply and demand. Thiscould be used to reduce future vulnerability, and to implement constitutional and legal reforms towards more efficient and effective water resources management in the region, as part of adaptation strategies to cope with

climate variability and change. Changes in agricultural productivity as a consequence of climate change are expected to have a great spatial variability, and while in SESA projections show that average productivity could be sustained or increased until the mid-century (SRES: A2, B2), in other regions increases in temperature and decreases in rainfall could decrease the productivity in the short-term (before 2025), threatening the food security of the poorest population. The great challenge for CA and SA will be to increase the food and bioenergy production and at the same time sustain the environmental quality in a scenario of climate change.

Renewable energy has a great potential for adaptation and mitigation. Hydropower is currently the main source of RE in CA and SA, followed by biofuels, notably bioethanol from sugarcane and biodiesel from soy. SESA is one of the main sources of production of the feedstocks for biofuels' production, mainly with sugarcane and soybean, and future climate conditions may lead to an increase in productivity and production. Advances in second generation bioethanol from sugarcane and other feedstocks will be important as a measure of adaptation, as they have the potential to increase biofuels productivity in the region. In spite of the large amount of arable land available in the region, the expansion of sugarcane and soy, related to biofuels production, might have some indirect land use change effects, producing teleconnections that could lead to deforestation in the Amazon and loss of employment in some countries. This would also also affect food security.

Climate variability and climate change are negatively affecting human health in CA and SA, either by increasing morbidity, mortality, and disabilities and through the emergence of diseases in regions previously non-endemic, or the re-emergence of diseases in areas where they have previously been eradicated or controlled. Climate-related drivers have been recognized for respiratory and cardiovascular diseases, vector- and water-borne diseases, mainly malaria, dengue and yellow fever. Vulnerabilities vary with geography, age, gender, race, ethnicity, and socio-economic status, and climate change and variability may exacerbate current and future risks to health.

Climate change would bring new environmental conditions resulting from modifications in space and time, and in the frequency and intensity, of weather and climate processes. The best way to be prepared to adapt to future climate change is by assisting people to cope with current climate variability, particurly to weather and climate extremes. Long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the CA and SA population. Such conditions weaken the importance of adaptation planning to climate change on the political agenda. In the present, there are few experiences on synergies between development, adaptation and mitigation planning, which can help local communities and governments to allocate available resources in the design of strategies to reduce vulnerability and to develop adapation measures. Facing a new climate system and, in particular, the exacerbation of extreme events, will call for new ways to manage human and natural systems for achieving ustainable development.

Frequently Asked Questions

FAQ 27.1: What is the impact of receding glaciers on natural and human systems in the tropical Andes?

Andean tropical glaciers retreat, with some fluctuations, started after the Little Ice Age (16^{th} to 19^{th} centuries) but the rate of retreat has accelerated since the middle of the 20^{th} century. Depending on the size and phase of glacier retreat there is an expected effect in terms of changes in runoff in basins fed from these glaciers. In an early phase of the glacier retreat runoff tends to increase due to an acceleration of glacier melt, but after a peak in discharge as the glacierized water reservoir gradually empties, runoff tends to decrease. This reduction in runoff is more evident during dry months when glacier melt is the major contribution to runoff. A reduction in runoff could reduce water related benefits and intensify conflicts among different users of water in high elevation Andean tropical basins which concentrates highly vulnerable populations. Glacier retreat has also been associated with disasters such as glacial lake outburst floods (GLOFS) that are a continuous threat in the region. And finally glacier retreat could have impacts on activities that rely on these high mountainous ecosystems such as alpine tourism, mountaineering and adventure tourism.

FAQ 27.2: Can PES be used as an effective way for helping local communities to adapt to climate change?

PES can be used as an effective way to help local communities to adapt to climate change. It can simultaneously help protect natural areas, while improving livelihoods and human well-being. However, during design and

planning, a number of factors at local level need to be taken into consideration in order to avoid potentially negative side effects. Reported setbacks include: poor definition if design should focus on actions or results, perception of commoditization of nature and its intangible values, inneficiency in reducing poverty, difficulties in building trust between parts involved in agreements, and eventual gender or land tenure issues.

FAQ 27.3: Are there emerging and re emerging human diseases as a consequence of climate variability and change in the region?

Climate variability and climate change (CC/CV) are negatively affecting human health in CA and SA, either by increasing morbidity, mortality, and disabilities (very high confidence), or by the emergence of diseases in previously non-endemic regions, or the re-emergence of diseases in areas where they have previously been eradicated or controlled (high confidence). Climate-related drivers have been recognized for respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), Hantaviruses and Rotaviruses, pregnancy-related outcomes, diabetes, chronic kidney diseases, and psychological trauma. It is very likely that CC/CV together augment current and future risks to health, amidst the region's vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, and pollution.

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Table 27-1: Regional observed changes in temperature, precipitation, river runoff and climate extremes in various sectors of CA and SA. Additional information on changes in observed extremes can be found in the IPCC SREX (Seneviratne *et al*., 2012) and Chapter 2 IPCC WGI AR5 [2.4, 2.5, 2.6]

Region	Period	Observed trends	References
CA and Northern SA			
Increase of precipitation in the NAMS during the onset season	1943-2002	+0.94 mm/day/58 years	Englehart and Douglas (2006)
Delay in the entire cycle of the summer NAMS reinfall in SW USA	1948-2004	-10 to -20 days/57 years	Grantz *et al*. (2007)
Positive rainfall trends during the summertime NAMS on the core region in the Southwest of USA.	1931-2000	17.6 mm century^{-1}	Anderson *et al*. (2010)
Positive trends in rainfall extremes (P95), mainly due to intense precipitation from tropical cyclones (TCs) in the NAMS	1961-1998	+1.3% decade^{-1}	Cavazos *et al*. (2008)
Increase of precipitation in the NAMS core region	1979-2008	+ 2 mm/day decade^{-1}	Wang *et al*. (2012)
Reduction in cold days and nights in CA and Northern SA	1951-2000	Cold days: -1 day decade^{-1} · Cold nights: -2 day decade^{-1}	Donat *et al*. (2013)
Increase warm days and nigts in Northern SA	1951-2000	Warm days: +2 to +4 day decade^{-1} · warm nights: +1 yo +3 day decade^{-1}	Donat *et al*. (2013)
Increase in heavy precipitation (R10) in Northern SA	1951-2000	+1 to +2 day decade^{-1} ·	Donat *et al*. (2013)
Reduction in consecutive dry days (CDD) in Northern SA	1951-2000	-2 day decade^{-1} ·	Donat *et al*. (2013)
Positive runoff trends of the Magdalena river in Colombia	1948-2008	+0.5 mm/day/50 years	Dai *et al*. (2009)
West Coast of SA			
SST and air temperatures off coast of Peru and Chile (15S-35S)	1960-2010	-0.25C/decade	Gutiérrez *et al*. (2011a; 2011b), Falvey and Garreaud (2009)
Cooling, reduction of precipitation, cloud cover, and number of rainy days since the middle 1970´s off coast of Chile (18S-30S)	1920-2009	-1 C/40 years, -1.6 mm/40 years, -2 octs/40 years, and -0.3 days/40 years	Schulz *et al*. (2011)
Reduction in the % of wet days until 1970, increase after that, reduction in the precipitation rate in southern Chile (37S-43S)	1900-2007	-0.34% until 1970 and +0.37 after that, -0.12 %	Quintana and Aceituno (2012)
Decrease in cold days and nights in all South American coast,	1951-2000	Cold days: -1 days decade^{-1}; cold nights: -2 days decade^{-1}	Donat *et al*. (2013)
Decrease in warm nights in all South American coast, increase in warm days in the northern coast of South America, decrease of warm days off the coast of Chile	1951-2000	Warm night: -1 days decade^{-1}; warm days: +3 days decade^{-1} ; warm days: -1 days decade^{-1}	Donat *et al*. (2013)
Increase of warm nights in the coast of Chile	1961-1990	+5 to +9%/31 years	Dufek *et al*. (2008)
Increase dryness as estimated by the Palmer Drought Severity Index (PDSI) for most of the west coast of SA (Chile, Ecuador, Northern Chile)	1950-2008	-2 to -4 / 50 years	Dai (2011)
Decrease in heavy precipitation (R95) in northern and central Chile	1961-1990	-45 to -105 mm/31 years	Dufek *et al*. (2008)
SESA			

Increase in mean annual air temperature in southern Brazil	1913-2006	+1.7 C/100 years	Sansigolo and Kayano (2010)
Decrease in the frequency of cold days and nights, increase in warm days in Argentina and Uruguay	1935-2002	-1.2%/decade, -1%/decade/, +0.2%/decade	Rusticucci end Renom (2008)
Increase in the highest annual maximum temperature and in the lowest annual minimum air temperature in Argentina and Uruguay	1956-2003	+0.8 C/47 years, +0.6C/47 years	Rusticucci and Tencer (2008)
Increase in the frequency of warm nights in Argentina and Uruguay and southern Brazil	1960-2009	10-20%	Rusticucci (2012)
Increase in warm nights in most of the region	1961-1990	+7 to +9%/31 years	Dufek *et al*. (2008)
Decrease in cold nights in most of the region	1961-1990	-5 to -9%/31 years	Dufek *et al*. (2008)
Decrease in cold days and nights in most of the region	1951-2000	warm nights: +3 days decade^{-1}; warm days: +4 days decade^{-1}	Donat *et al*. (2013)
Increase in warm days and nights in most of the region	1951-2000	Cold nights: -3 days decade^{-1}; cold days: -3 days decade^{-1}	Donat *et al*. (2013)
Increase of consecutive dry days (CDD) in northern Argentina, northern Chile, Bolivia and Paraguay and decrease of CDD in SA South of 30 S	1961-1990	+15 to +21 days/31 years, -21 to -27 days/31 years	Dufek *et al*. (2008)
Reduction in the number of dry months during the warm season October-March in the Pampas region between 25S-40S	1904-2000	From 2-3 months in 1904-1920 to 1-2 months from 1980-2000	Barrucand *et al*. (2007)
Increase in moister conditions as estimated by the Palmer Drought Severity Index (PDSI) in most of SESA	1950-2008	0 to 4/50 years	Dai (2011)
Positive rainfall trends in the Parana River	1948-2008	+1.5 mm/day/50 years	Dai *et al*. (2009)
Positive rainfall trends in the Parana River Basin	1948-2008	+1.5 mm/day/50 years	Dai *et al*. (2009)
Increase in number of days with precipitation bove 10 mm (R10) in most of the region	1951-2000	+2 days/decade^{-1}	Donat *et al*. (2013)
Increase in heavy precipitation (R95) in most of the region	1951-2000	+1% decade $^{-1}$	Donat *et al*. (2013)
Increase in consecutive dry days	1951-2000	-4 days decade $^{-1}$	Donat *et al*. (2013)
Increase in heavy precipitation (R95) in most of the region	1961-1990	+45 to +135 mm/31 years	Dufek *et al*. (2008)
Increase in heavy precipitation (R95) in the state of Sao Paulo	1950-1999	+50 to +75 mm/40 years	Dufek and Ambrizzi (2008)
Decrease in consecutive dry days (CDD) in the state of Sao Paulo	1950-1990	-25 to-50 days/40 years	Dufek and Ambrizzi (2008)
Lightning activity increases significantly with increasing temperature in the state of Sao Paulo	1951-2006	+40% per 1_C for daily and monthly timescales and approximately 30% per 1_C for decadal timescale	Pinto and Pinto (2008)
Increase in the number of days with rainfall above 20 mm in the city of Sao Paulo	2005-2011	+5 to +8 days/11 years	Marengo *et al*. (2012a), Silva Dias *et al*. (2012)
Increase in excess rainfall events duration after 1950	1901-2003	+ 21 months/53 yars	Krepper and Zucarelli (2010b)
Decrease in dry events and events of extreme dryness from 1972 to 1996	1900-2005	-29 days/24 years	Vargas *et al*. (2011)
Andes			
Increase in mean maximum temperature along the Andes, and increase in the number of frost dates	1921-2010	+0.10-12 C /decade in 1921-2010, and +0.23-0.24 C/decade during 1976-2010; 8	Marengo *et al*. (2011b)

		days/decade during 196-2002	
Increase in air temperature and changes in precipitation Northern Andes (Colombia, Ecuador)	1961-1990	+0.1 C to +0.22 C/decade, -4 to +4 %/decade years	Villacís (2008)
Increase in temperature and precipitation in northern and central Andes of Peru	1963-2006	+0.2-0.45C/decade, -20 to -30%/40 years	SENAMHI (2005; 2007; 2009a; 2009c; 2009d)
Increase in temperature and changes in precipitation in the southern Andes of Peru	1964-2006	+0.2 to 0.6 C/decade, -11 to +2 mm/decade	SENAMHI (2007; 2009a; 2009b; 2009c; 2009d); Marengo *et al*. (2011b)
Increase in air temperature and rainfall reduction Argentinean and Chilean Andes and Patagonia	1950-1990	+0.2 to 0.45 C/decade, -10 to -12%/decade	Falvey and Garreaud (2009), Masiokas *et al*. (2008), Villalba *et al*. (2003)
Decrease in number of days with rainfall above 10 mm (R10)	1950-2000	-3 days decade^{-1}	Donat *et al*. (2013)
Increase in dryness in the Andes between 35.65 S-39.9 S using the PDSI	1950-2003	-7 PDSI/53 years	Christie *et al*. (2011)
Strong rainfall decrease in the Mantaro Valley, central Andes of Peru	1970-2005	-44 mm/decade	SENAMHI (2009c)
Increase in air temperature in Colombian Andes	1959-2007	+1 C/20 years	Poveda and Pineda (2009)
Amazon region			
Decadal variability of rainfall in northern and southern Amazonia	1920-2008	-3 STD/30 years in northern Amazonia and +4 STD/30 years in southern Amazonia since the middle 1970's	Marengo *et al*. (2009a), Satyamurty *et al*. (2010)
Decrease in rainfall in all the region	1975-2003	-0.32 %/28 years	Espinoza *et al*. (2009a; 2009b)
Delay on the onset of the rainy season in southern Amazonia	1950-2010	-1 month since 1976 to 2010	Butt *et al*. (2011), Marengo *et al*. (2011b)
Increase of precipitation in the SAMS core region	1979-2008	+ 2 mm/day decade^{-1}	Wang *et al*. (2012)
Onset becomes steadily earlier from 1948 to early 1970s, demise dates have remained later, and SAMS duration was longer after 1972.	1948-2008	SAMS from 170 days (1948–1972) to 195 days (1972–1982).	Carvalho *et al*. (2011)
Spatially varying trends of heavy precipitation (R95), increase in many areas and insufficient evidence in others	1961-1990	+100 mm/31 years in western and extreme eastern Amazonia,	Marengo *et al*. (2009a)
Spatially varying trends in dry spells in (CDD), increase in many areas and decrease in others	1961-1990	+15 mm/31 years in western Amazonia, -20 mm/ in southern Amazonia	Marengo *et al*. (2009a; 2010)
Negative runoff trends of the Amazon River	1948-1968	-1.5 mmday/50 years	Dai *et al*. (2009), Dai (2011)
Positive runoff trends of the Tocantins River	1948-1968	+0.5 mmday/50 years	Dai *et al*. (2009), Dai (2011)
Positive rainfall trends in most of Amazonia and negative trends in western Amazonia	1948-2008	+1 mm/day/50 years, -1.5 mm/day/50 years	Dai *et al*. (2009), Dai (2011)
Increased dryness as estimated by the Palmer Drought Severity Index PDI in southern Amazonia and moister conditions in western Amazonia	1950-2008	-2 to -4/50 years, +2 to +4 /50 years	Dai (2011)
Decrease of seasonal mean convection and cloudiness	1984-2007	+30 W/m2/23 years, -8 %/23 years	Arias *et al*. (2011)
Delayed onset of rainy season in southern Amazonia due to land use change	1970-2010	-0.6 days/30 years	Butt *et al*. (2011)

Northeast Brazil			
Negative runoff trends in the Sao Francisco River	1948-2008	-2 mm/day/50 years	Dai *et al*. (2009), Dai (2011)
Negative rainfall trends interior Northeast Brazil and positive trends in northern Northeast Brazil	1948-2008	-0.3 mm/day/50 years, +1.5 mm/day/50 years	Dai *et al*. (2009), Dai (2011)
Positive trends in heavy precipitation (R95) in some areas, negative trends in others in southern Northeast Brazil	1970-2006	-2 mm/24 years to + 6 mm/24 years,	Silva and Azevedo (2008)
Negative trends in consecutive dry days CDD in most of southern Northeast Brazil	1970-2006	-0.99 days/24 years	Silva and Azevedo (2008)
Increase in total annual precipitation in northern Northeast Brazil	1970-2006	+1 to +4 mm/year/24 years	Santos and Brito (2007)
Spatially varying trends in heavy precipitation (R95) in northern Northeast Brazil	1970-2006	-0.1 to +5 mm/yeas/24 years	Santos and Brito (2007)
Spatially varying trends in heavy precipitation (R95) and consecutive dry days (CDD) in northern Northeast Brazil	1935-2006	-0.4 to +2.5 mm/year/69 years, -1.5 to +1.5 days/year/69 years,	Santos *et al*. (2009)
Increase dryness in Southern Northeast Brazil as estimated by the PDSI, and moister conditions in northern Northeast Brazil	1950-2008	-2 to -4/50 years, 0 to +1/50 years	Dai (2011)

Table 27-2: Regional projected changes in temperature, precipitation, river runoff and climate extremes in different sectors of CA and SA. Various studies used A2 and B2 scenarios from CMIP3 and various RCPs scenarios for CMIP5, and different time slices from 2010 to 2100. In order to make results comparable, the CMIP3 and CMIP5 at the time slice ending in 2100 are included. Additional information on changes in projected extremes can be found in the IPCC SREX (see IPCC, 2012), and Chapters 9 and 14 from IPCC WG1AR5 [9.5, 9.6 and 14.2, 14.7]

Region	Models and scenarios	Projected changes	References
CA and Northern SA			
Decrease in LAI, increase in evapotranspiration by 2070-2099 in CA	23 CMIP3 models, A2	Evapotransp: +20%; LAI:-20%+0.94 mm/day/58 years	Imbach *et al*. (2012)
Increases in temperature by 2075 and 2100 in CA	9 CMIP3 models, A2	+2.2 C by 2075; +3.3 C by 2100	Aguilar *et al*. (2009)
Rainfall reductions in CA, and increases in Venezuela. Increase in air temperature in the region	20 km MRI JMA model, A1B	Rainfall decrease/increase of about -10%/+10%, by 2079. Temperature increases of about +2.5-+3.5 C by 2079	Hall *et al*. (2009)
Decrease in precipitation and increase of evaporation was projected to increase in most of the region. Soil moisture in most land areas were projected to decrease in all seasons.	20 km MRI JMA model, A1B	Precipitation decrease of about -5 mm/day, evaporation increase of about +3 to +5 mm/day; soil moisture to decrease by -5 mm/day.	Nakaegawa *et al*. (2013)
Rainfall reductions in Nicaragua, Honduras, Northern Colombia and Northern Venezuela, increases in Costa Rica and Panama. Temperature increases in all region by 2071-2100	PRECIS forced by the HadAM3, A2	Rainfall: -25 to -50%, and +25 to +50%. Temperature: +3 to +6 C	Campbell *et al*. (2011)
Increase of precipitation and temperature in northern SA, decrease in interior Venezuela, temperature increases by 2071-2100	Eta forced with HadCM3, A1B	Increases by +30 to 50%, and reductions between -10 to -20%; temperature: +4 to +5 C;	Marengo *et al*. (2011a)
Reduction in precipitation and temperature increases by 2100 in CA	PRECIS forced with HadAM3, A2	Precipitation: -24 to -48%; temperature: +4 to -5 C	Karmalkar *et al*. (2011)
Increase in warm nights, consecutive dry days and reduction in heavy precipitation in Venezuela, by 2100	PRECIS forced with HadAM3, A2	Increase by +12 to _18%, +15 to +25 days and reduction of 75 to 105 days	Marengo *et al*. (2009a; 2010)
Increase in temperature, decrease in precipitation by 2100	23 CMIP3 models, A1B	Incfease by +3 to +5 C; reduction by -10 to -30%	Giorgi and Diffenbaugh (2008)
Increase in consecutive dry days and in heavy precipitation by 2099	20 km JMA-MRI model, A1B	Increase by +5 days and bdtwen +2 to +8 %	Kamiguchi *et al*. (2006)
West Coast of SA			
Decrease of precipitation, runoff and increase of temperature at the Limari river basin in semi-arid Chile by 2100	PRECIS forced with HadAM3, A2	Precipitation: -15 % to -25%; runoff: -6 to -27%; temperature: + 3 to +4 C	Vicuña *et al*. (2011)

Warming and increase of surface winds in west coast of SA (Chile) by 2100	15 CMIP3 models, PRECIS forced with HadAM3, A2	Temperature: +1 C; coastal winds: +1.5 m/sec	Garreaud and Falvey (2009)
Precipitation increase in the bands 5N-10S, and 25S-30S, reduction between 10S-25S and 30S-50S; temperature increase between by 2100	Eta model forced with HadCM3, A1B	Increases of 30-40%, rediction of 10-20%; increases of 3-5 C	Marengo *et al*. (2011a)
Increase in warm nights, reduction in consecutive dry days, and increase in heavy precipitation in 5N-5S by 2100	PRECIS forced with HadAM3, A2	Increase of +3 to +18%, rediction of -5 to – 8 days, increase by +75 to +105 days	Marengo *et al*. (2009a; 2010)
Increase of air temperature, increase of precipitation between 0 and 10S, reduction between 20 and 40S by 2100	23 CMIP3 models, A1B	Increase of -2 to -3 C; increase by 10%, reduction by -10 to -30%	Giorgi and Diffenbaugh (2008)
Increase of consecutive dry days between 5 N and 10 S and south of 30S, increase of heavy precipitation between 5S-20S and south of 20S by 2099	20 km MRI JMA, A1B	Increase by 10 days and between +2 to +10%	Kamiguchi *et al*. (2006)
Decrease of precipitation between 15 and 35 S and increase south of 40S, increase of precipitation by 2100	MM5 forced with HadAM3, A2	Decrease of -2 mm/day, increase of 2 mm/day, increase of +2.5 C	Nuñez *et al*. (2009)
Decrease of precipitation in Panama and Venezuela, increase of heavy precipitation in Panama and reduction in Venezuela, reduction of consecutive dry days over Panama and Colombia by 2099	RCA forced with ECHAM5-MPI OM model, A1B	Reduction of -1 to -3 mm/day,	Sörensson *et al*. (2010)
SESA			
Increase in precipitation and runoff, an in air temperature by 2100	Eta forced with HadCM3, A1B	Precipitation: + 20 to +30%; Runoff: +10 to +20%; air temperature: 2.5 to 3.5 C	Marengo *et al*. (2011a)
Increases in precipitation and temperature in the La Plata basin by 2050	MM5 forced with HadAM3, A2	Precipitation: _+0.5 to 1.5 mm/day; temperature: +1.5 C to 2.5 C.	Cabré *et al*. (2010)
Increase in warm nights, consecutive dry days and heavy precipitation by 2100	7 CMIP3 models, A1B	Warm nights: +10 to +30%; Consecutive dry days: +1 to +5 days; Heavy precipitation: +3 to +9 %.	Menendez and Carril (2010)
Increase in precipitation during summer and spring, and reduction in fall and winter by 2100	9 CMIP3 models, A2	Increase pof + 0.4 to +0.6 mm/day, reduction of -0.02 to -0.04 mm/day	Seth *et al*. (2010)
Increase in warm nights, consecutive dray days and heavy precipitation by 2100	PRECIS forced with HadAM3, A2	Increase of +6 to +12%, +5 to +20 days, +75 to +105 days	Marengo *et al*. (2009a; 2010)
Increase in temperature and rainfall by 2100	23 CMIP3 models, A1B	Increase by +2 to _+4 C, increase by +20 to +30 %	Giorgi and Diffenbaugh (2008)
Increase in consecutive dry days and in heavy precipitation by 2099	20 km MRI-JMA model, A1B	Increase by +5 to +10% and by +2 to +8 %	Kamiguchi *et al*. (2006)

Increase of precipitation in north central Argentina, decrease in southern Brazil, increase of air temperature by 2100	MM5 forced with HadAM3, A2	Increase of +_0.5 to +1 mm/day, reduction of -0.5 mm/day, increase of +3 to +4.5 C	Nuñez *et al*. (2009)
Increase of precipitation, heavy precipitation, reduction of consecutive dry days in the eastern part of the region, increase in the western part of the region by 2099	RCA forced with the ECHAM5 mode, A1B	Increase of +2 mm/day, of +5 to +15 mm, reduction of -10 days and incrarse of +5 days	Sörensson *et al*. (2010)
Andes			
Reduction of precipitation and temperature, increase by 2100 in the Altiplano	11 CMP3 models, A2	Precipitation: -10 to -30 %; temperature:>3 C	Minvielle and Garreaud (2011)
Precipitation increase at 5N-5S, and 30S-45 S, decrease at 5-25 S; temperature increases by 2100	Eta forced with HadCM3, A1B	Increase between +10 and +30%, decrease by -20 t -30%, increase of +3.5 to 4.5 C	Marengo *et al*. (2011a)
Increase in warm nights, reduction of heavy precipitation and consecutive dry days south of 15 S by 2100	PRECIS forced with HadAM3, A2	Increase by +3 to +18%, reduction by -10 to -20 days, and -75 to -105 days	Marengo *et al*. (2009a)
Increase in temperature, rainfall increase between 0-10S and reduction between 10-40 S	23 CMIP3 models, A1B	Increase by +3 to +4 C, increase by 10% and reduction by -10%	Giorgi and Diffenbaugh (2008)
Reduction of consecutive dry days and increase of heavy precipitation by 2099	20 km MRI-JMA model, A1B	Reduction by -5 days, increase by +2 to +4 % south of 20S	Kamiguchi *et al*. (2006)
Increase in precipitation, heavy precipitation, and consecutive dry days by 2070-99	RCA forced with ECHAM5, A1B	Increases of +1 to +3 mm/day, +5 mm and of +5 to +10 days	Sörensson *et al*. (2010)
Reduction in summer precipitation and increase in surface air temperature in the Altiplano region by 2099	9 CMIP3 models, A2	Reduction in precipitation between -10% and -30%, an temperature increase of +3 C	Minvielle and Garreaud (2011)
Amazon region			
Rainfall reduction in central and eastern Amazonia, increase in western Amazonia, warming in all region by 2100	Eta forced with HadCM3, A1B	Precipitation: -20 top -30%, +20 to +30%; temperature: +5 to +7 C	Marengo *et al*. (2011a)
Reduction in the intensity of the South Atlantic Convergence Zone and in rainfall in the South American monsoon region, 2081-2100	10 CMIP3 models, A1B	Precipitation: -100 to -200mm/20 years	Bombardi and Carvalho (2009)
Small increases of precipitation in western during summer and decreases in winter in Amazonia by 2100	5 CMIP3 models, A2 and ANN	+1.6% in summer and -1.5% in winter	Mendes and Marengo (2010)
Increase in the number of South American Low Level Jet east of the Andes events (SALLJ), and in the moisture transport from Amazonia to the La Plata basin by 2090	PRECIS forced by HadAM3, A2	+50 events of SALLJ during summer, increase in moisture transport by 50%	Soares and Marengo (2009)
Increase of precipitation in the South American monsoon during summer and spring, and reduction during fall and winter by 2100	9 CMIP3 models, A2	Increase of +0.15 to +0.4 mm/, reductions of -0.10 to -0.26 mm/day	Seth *et al*. (2010)

Increase in warm nights, increase of consecutive dry days in eastern Amazonia, increase of heavy precipitation in western Amazonia and reduction in eastern Amazonia by 2100	PRECIS forced with hadAM3, A2	Increase of +12 to +15%, by 25-30 days in eastern Amazonia, increase in western Amazonia by 75-105 days and rediction by -15 to 75 days in eastern Amazonia	Marengo *et al*. (2009a)
Increase in air temperature, rainfall increase in western Amazonia and decrease in eastern Amazonia by 2100	CMIP3 models, A1B	Increase of +4 to +_6 C, increase of +10% and decresase between -10 to -30%	Giorgi and Diffenbaugh (2008)
Reduction of consecutive dry days and increase in heavy precipitation by 2099	20 km MRI-JAM model, A1B	Reduction of -5 to -10 days, increase by +2 to +8 %	Kamiguchi *et al*. (2006)
Early onset and late demise of the rainy season in SAMS by 2040-2050 relative to 1951-80	10 CMIP5 models, RCP8.5 (high emission)	Onset 14 days earlier than present, demise 17 days later than present	Jones and Carvalho (2013)
Increase precipitation in SAMS during the monsoon wet season in 2071-2100 relative to 1951-80	10 CMIP5 models, RCP8.5 (high emission)	Increase of 300 mm during the wet season	Jones and Carvalho (2013)
Increase of precipitation in western Amazonia, reduction of heavy precipitation in northern Amazonia and increase in southern Amazonia, reduction of consecutive dry days in western Amazonia and increase in eastern Amazonia by 2099	RCA forced with the ECHAM5 mode, A1B	Increase of +1 to +_3 mm/day, reduction of -1 to -3 mm, in crease of +5 to _10 mm, decrease of -5 to -10 days, increase by +20 to +30 days	Sörensson *et al*. (2010)
Northeast Brazil			
Rainfall reduction in the entire region, temperature increases by 2100	Eta forced with HadCM3, A1B	Precipitation: -20 to -20%; temperature: +3 to +4 C	Marengo *et al*. (2011a)
Increase of warm nights, of consecutive dry days, and reduction of heavy precipitation by 2100	PRECIS forced with HadAM3, A2	Increase by +18 to +24%, by +25 to +30 days and -15 to –75 days	Marengo *et al*. (2009a)
Increase in temperature, reductions in precipitation by 2100	23 CMIP3 models, A1B	Increase of +2 to +4 C, reduction of -10 to -30%	Giorgi and Diffenbaugh (2008)
Reduction of consecutive dry days and increase in heavy precipitation by 2099	20 km MRI-JMA model, A1B	Reduction of -5 to -10% and increase of +2 to +6 %	Kamiguchi *et al*. (2006)
Increase of precipitation, in heavy precipitation and consecutive dry days by 2099	RCA foeced with ECHAM5 model, A1B	Increase of +1 to +2 mm/day, increase by +5 to +10 mm, and increase by +10 to +30 days	Sörensson *et al*. (2010)

Table 27-3: Observed trends related to Andean cryosphere.
a) Andean tropical glacier trends since the Little Ice Age (LIA) maximum and, particularly, during the last decades

Country	**Documented massifs (latitude)**	**Significant changes recorded and reference** (dates in AD)	**References**
Venezuela	*Cordillera de Merida (10°N)*	Four glacial advances between 1250 and 1810. Glaciers have been rapidly retreating since at least 1870. Equilibrium Line Altitude (ELA) raised up by ~300-500m between LIA maximum and today. Accelerated melting since 1972. Remaining glaciers are at risk of disappearing completely in the next years since ELA lies near to the Pico Bolivar summit (4979m).	Polissar *et al*. (2006); Morris *et al*. (2006)
Colombia	*Parque Los Nevados (4°50N)* *Sierra Nevada del Cocuy 56°30N)* *Sierra Nevada de Santa Marta (10°40N)*	LIA maximum occurred between 1600 and 1850. Loss of 60-84% in glacierized areas during the 1850-2000 period and many small/low elevation glaciers have disappeared. In the past 50yrs, 50% of glacier areas have been lost, and in the past 15yrs 10-50%. Since 2000, glaciers retreated at a rate of 3.0km^2/yr. Glacier areas total 45km^2 in Colombia in 2011.	Ruiz *et al*. (2008); Ceballos *et al*. (2006); Poveda and Pineda (2009)
Ecuador	*Antisana (0°28S)* *Chimborazo and Carihuayrazo (1°S)* *Ecuadorian volcanoes*	LIA maximum occurred in around 1720 and 1830 (Chimborazo). Historical evidences of ELA at 4700±50m in around 1740. ELA raised up 300m between the middle 18th and the last decades of the 20th (~200m during only the 20thcentury). A slight glacier reduction was reported between 1956 and 1976, but in the 1976-2006 period, glacier areas lost ~45%. Glaciers at low elevation (<5300m) are in process of extinction. Glaciers in Ecuador total less than 50km^2 in 2011.	Francou (2004); Jordan *et al*. (2005); Jomelli *et al*. (2009); Cáceres *et al*. (2006)
Peru	*Cordillera Blanca (9°S)*	LIA maximum occurred in around 1630±27. Loss of 12-17% of glaciers during the 18th century, and 17-20% during the 19th. Rapid retreat in the 1930s-1940s and from 1976-80. ELA increased by ~100m from the LIA maximum to the beginning of the 20th century, and by more than 150m during only the 20th century. The lost of glacial area reported by several teams since the 1960s to the 2000s converge on a range of 20-35% Physical observations of the Yanamarey glacier show acceleration in frontal retreat at a rate of 8 m decade^{-1} since 1970, accompanied by total volume loss on the order of 0.022 km Increase of 1.6 (± 1.1) percent in the specific discharge of the more glacier-covered catchments (>20 percent glacier area) Seven out of nine watersheds exhibit decreasing dry-season discharge. Median (out of 9 glaciers analyzed) average ice area loss of 0.61% a^{-1}. Glaciers of Coropuna have retreated by 26% between 1962 and 2000	Kaser and Georges (1997); Georges (2004); Mark and Seltzer (2005); Silverio and Jaquet (2005); Raup *et al*. (2007) Jomelli *et al*. (2009); UGHR (2010); Bury *et al*. (2011) Mark *et al*. (2010); Baraer *et al*. (2012)
	Coropuna volcano (15°33S)	Glaciers of Coropuna receded by 26% between 1962 and 2000	Racoviteanu *et al*. (2007)
	Cordillera Vilcanota (13°55S)	Qori Kalis glacier receded in the 1991-2005 period 10 times faster than during the 1963-2005 period	Thompson *et al*. (2006; 2011)

Bolivia	*Cordillera Real and Cordillera Quimza Cruz (16°S)*	On the Telata glacier, strong melting after the maximum extent occurred from 10.8±0.9 to 8.5±0.4kyr ago, followed by a slower retreat until the Little Ice Age, about 200 years ago. The LIA maximum is dated between 1657±20 and 1686±20 in the north of Bolivia. Between the LIA maximum and the late 20th century, the ELA increased by 300m (180-200m during the only 20th century). Proxy of vertical englacial temperature in Bolivia (Illimani, 6340m, 16°S) shows two warming phases from AD 1900 to 1960 (+0.5±0.3 K) starting in 1920-1930 and from 1985 to 1999 (+0.6±0.2K), corresponding to a mean atmospheric temperature rise of 1.1±0.2 K over the 20th century. From 1956 to 1963-1976, glaciers were near the equilibrium, but the recession was very strong after 1976. Small glaciers at low elevation (<5300-5400m) are in process of extinction (Chacaltaya vanished in 2009). Since 1991, Zongo glacier (6000-4900m) has lost a mean of 0.4m we/yr and only 20% of the mass balances measured in the 1991-2011 period have been positive or near the equilibrium. Glaciers of the Cordillera Real have lost 43% of their volume between 1963 and 2006, essentially over the 1976-2006 period, and 48% of their surface area between 1976 and 2006. Studies of sensitivity have shown that during the October-March wet period, crucial for the year mass balance, +1°C temperature increases the ELA by ~200m.	Jomelli *et al*. (2011) Rabatel *et al*. (2005) Rabatel *et al*. (2006; 2008); Gilbert *et al*. (2010); Soruco *et al*. (2009)*;* Lejeune (2007)
	Sur Lipez, Caquella, 21°30S	Evidence of recent degradation of Caquella rock glacier	Francou *et al*. (1999)

b) Extra tropical Andean cryposphere (glaciers, snowpack, runoff effects) trends.

Region	Documented massifs/latitude	Significant changes recorded and reference	References
Andes of Chile, Argentina and Bolivia and Argentinan Patagiona	*Snow cover extent*	The 1979–2006 period shows a sinusoidal like pattern for both snow cover and snow mass, though neither trend is significant at the 95% level.	Foster *et al*. (2009)
Dessert Andes *(17°S-31°S)*	*Review on extra tropical glaciers*	Most areas in the Andes of extratropical SA have experienced a general pattern of glacier recession and significant ice mass losses	Masiokas *et al*. (2009)
	Huasco basin glaciers (29°S)	Glacier mass loss is evident over the study period, with a mean of –0.84m w.e. yr–1 for the period 2003/2004–2007/2008	Nicholson *et al*. (2009); Rabatel *et al*. (2011); Gascoin *et al*. (2011)
Central Andes *(31°S-36°S)*	*Review on extra tropical glaciers*	Most areas in the Andes of extratropical SA have experienced a general pattern of glacier recession and significant ice mass losses	Masiokas *et al*. (2009)
	Piloto/Las Cuevas (32°S)	Within the 24-year period, 67% of the years show negative net annual specific balances, with a cumulative mass balance loss of - 10.50 m w.e.	Leiva *et al*. (2007)
	Aconcagua basin glaciers (33°S)	Reduction in glacier area of 20% ($0.63 km^2 a^{-1}$) over last 48 years. Glaciar Juncal Norte, exhibits a smaller reduction (14%) between 1955 and 2006.	Nicholson *et al*. (2009); Bown *et al*. (2008)
	Central Andes glaciers (33–36 °S)	All studied glaciers exhibited a negative trend during the 20th century with mean frontal retreats between –50 and $–9 my^{-1}$, thinning rates between 0.76 and 0.56 my^{-1} and a mean ice area reduction of 3% since 1955.	Le Quesne *et al*. (2009)
	ELA across central Andes	Analysis of radiosonde data of central Chile shows mid-tropospheric warming with an elevation increase of the 0ºC isotherm of 122 ± 8 m and 200 ± 6 m in winter and summer, respectively, during the 27-year period between 1975 and 2001.	Carrasco *et al*. (2005)
	Snowpack (30 °S -37°S)	Marked interannual variability, and a positive, though nonsignificant, linear trend for period (1951–2005)	Masiokas *et al*. (2006)
	Morenas coloradas rock glacier (32 °S -33°S)	A significant change in the active layer and suprapermafrost possibly associated with warming processes.	Trombotto and Borzotta (2009)
	Mendoza river streamflow	Possible link to rising temperatures and snowpack/glacier effects. Not conclusive.	Vich *et al*. (2007)
	Aconcagua basin streamflow	Significant decrease in streamflow that could be explained by a progressive change in glaciers area and volume in the basin.	Pellicciotti *et al*. (2007)
	Streamflow from basins between 28 °S and 47 °S	Not significant increase in February run-off trends for period 1950–2007 that might suggest an increase of glacier melt in the Andes.	Casassa *et al*. (2009)
	Streamflow timing between 30 °S and 40 °S	Significant (95% confidence level) negative trend (CT date shifting towards earlier in the year) for 23 out of the 40 analyzed series. More relevant is precipitation rather than temperature.	Cortés *et al*. (2011)

Patagonian Andes *(36°S-55°S)*	*Review on extra tropical glaciers*	Most areas in the Andes of extratropical SA have experienced a general pattern of glacier recession and significant ice mass losses	Masiokas *et al*. (2009)
	Casa Pangue glacier (41°S)	Between 1961 and 1998, mean thinning rate of -2.3 ± 0.6 m a^{-1}. When ice thinning is computed for the period between 1981 and 1998, the resulting rate is 50%higher (-3.6 ± 0.6 m a^{-1}).	Bown and Rivera (2007)
	North Patagonian Icefield (NPI)	Glacial lake outburst flood (GLOF) interpreted as a delayed paraglacial response to the retreat of Calafate glacier during the twentieth century.	Harrison *et al*. (2006)
	Southern Patagonia Icefield (SPI)	Retreating glaciers with larger rates observed on the west side coinciding with lower elevations of the ELAs (relative to the east side).	Barcaza *et al*. (2009)
	NPI, SPI and the Cordillera Darwin Icefield (CDI)	The majority of glaciers have retreated between 1945 and 2005 with maximum values of 12.2 km for Marinelli Glacier in the CDI, 11.6 km for O'Higgins Glacier in the SPI and 5.7 km for San Rafael Glacier in the NPI	Lopez *et al*. (2010)
	Cordón Martial glaciers (54 °S)	Ice loss rate for the period April 2002-December 2006 of 27.9 ± 11 km3/year, equivalent to an average loss of -1.6 m/year of ice thickness.	Chen *et al*. (2007)
	Gran Campo Nevado (GCN) (53 °S)	Glaciers slowly reciding from Late Little Ice Age (LLIA). Acceleration started 60 years ago	Strelin and Iturraspe (2007)
		All major glaciers of the GCN show a significant glacier retreat during the last 60 yr. Some of the outlet glaciers lost more than 20% of their total area during this period. Overall glacier retreat amounts to 2.8% of glacier length per decade and the glacier area loss is 2.4% per decade in the period from 1942 to 2002.	Schneider *et al*. (2007)
	Proglacial lakes located in Andean Patagonia between ~40°S and ~50°S	Summertime negative trend on lakes with a direct influence of glaciers interpreted as an indication that melt water is decreasing because the ice volume reduction.	Pasquini *et al*. (2008)
	Northwestern Patagonia between ca. 38° and 45°S.	Recession of 6 glaciers based on areal photograph analysis.	Masiokas *et al*. (2008)
	Streamflow from basins between 28 °S and 47 °S	Not significant increase in February run-off trends for period 1950–2007 that might suggest an increase of glacier melt in the Andes.	Casassa *et al*. (2009)

Table 27-4: Synthesis of projected climate change impacts on hydrologic variables in large South American basins and major glaciers.

Region	Basins studied	Hydrologic Variable	Projected Change	Period	GCM	Scenarios	References
La Plata Basin and SESA	Paraná	Runoff	Runoff: + 4.9% (not robust) Runoff: +10 to +20%	2081-2100 2100	CMIP3 Eta forced with HadCM3	A1B A1B	Nohara *et al.* (2006) Marengo *et al.* (2011a)
	Carcarañá	ET, Recharge	Increase in ET not compensated with increase in precipitation, slight reduction in recharge.	2010-2030	HadCM3	A2	Venencio and García (2011)
	Grande (Parana)	Runoff	Range from +20 to -20%	Different periods	7 CMIP3 models	Prescribed temperature changes and emission scenarios	Todd *et al.* (2011) ; Gosling *et al.* (2011); Nóbrega *et al.* (2011)
	Itaipu (Parana)	Runoff	2010–2040: Left bank: –5 to –15%; Right bank: +30% 2070-2100: 0 to –30%	2010–2040 and 2070-2100	CCCMA-CGCM2	A2	Rivarola *et al.* (2011)
Amazon Basin	Peruvian Amazon–Andes basin	Runoff	Some basins increased, some reduced	Three time slices	BCM2, CSMK3 and MIHR	A1B, B1	Lavado Casimiro *et al.* (2011)
	Ecuador - Tomebamba/Paute	Runoff	Some scenarios increase and some reduction	2070-2100	CMIP3	A1B	Buytaert *et al.* (2011)
	Amazon at Obidos	Runoff	Average change + 5.4% (not robust)	2081-2100	CMIP3	A1B	Nohara *et al.* (2006)
		Runoff	+6%	2000-2100	ECBilt-CLIO-VECODE	A2	Aerts *et al.* (2006)
	Amazon -Orinoco	Runoff	-20%	2050s	HadCM3	A2	Palmer *et al.*(2008)
Tropical Andes	Colombian glaciers	Glacier extent	Glacier disappearance by 2020s	linear extrapolation			Poveda and Pineda (2009)
	Cordillera Blanca basins	Runoff	Increase for next 20-50 years, reduction afterwards	2005-2020	Temperature output only	B2	Chevallier *et al.* (2011)
		Glacier extent	2050: area is reduced by 38 to 60%. Increased seasonality 2080: area is reduced by 49 to 75%. Increased seasonality	2050 (climatology)	Not specified	A1, A2, B1, B"	Juen *et al.* (2007)
	Basins providing water to cities of Bogota, Quito, Lima and La Paz	Water availability	Inner tropics: Only small change because of an offset of an increase in precipitation by an increase in evapotranspiration. Outer tropics: severe reductions due to a decrease in precipitation and increase in evapotranspiration	2010-2039 and 2040-2069	19 CMIP3 models	A1B and A2	Buytaert and De Bièvre (2012)

Central Andes	Maipo	Runoff Unmet demand	Reduction up to 30% Unmet demand up to 50%	Three 30-year periods 2070-2090	HadCM3	A2, B2	Melo *et al*. (2010); ECLAC (2009a) Meza *et al*. (2012)
	Maule, Laja	Runoff	Reduction up to 30%	Three 30-year periods	HadCM3	A2, B2	McPhee *et al*. (2010); ECLAC (2009a)
	Bio Bio						Stehr *et al*. (2010)
	Limari	Runoff	Reduction range -20 to -40%. Change in seasonality	2070-2100	HadCM3	A2, B2	Vicuña *et al*. (2011)
	Limay	Runoff	Reduction range -10 to -20%.	2080s (climatology)	HadCM2	Not specified	Seoane and López (2007)
North East Brazil	Brazilian Federal States of Ceara´ and Piauı´	Runoff	No significant change up to 2025. After 2025: strong reduction with ECHAM4; slight increase with HadCM2.	2000-2100	HadCM2, ECHAM4	Not clear	Krol *et al*. (2006); Krol and Bronstert (2007)
	Paracatu (Sao Francisco)	Runoff	A2: +31 to +131%; B2: no significant change	2000-2100	HadCM3	A2, B2	De Mello *et al*. (2008)
	Jaguaribe	Demand	Increase in demand: +33 to +44%	2040	HadCM3	A2, B2	Gondim *et al*. (2008)
	Parnaiba	Runoff	-80%	2050s	HadCM3	A2	Palmer *et al*. (2008)
	Mimoso catchment	Runoff	Dry scenario: -25 to -75%; Wet scenario: +40 to + 140%; Similar changes in GW recharge	2010–2039, 2040–2069, and 2070–2099	CSMK3 and HadCM3	A2, B1	Montenegro and Ragab (2010)
	Tapacurá River	Runoff	Low emission: decrease by 4.89%, 14.28% and 20.58% High emission: increase by 25.25%, 39.48% and 21.95%	Three 30-year periods	CSMK3 and MPEH5	A2, B1	Montenegro and Ragab (2012)
	Benguê catchment	Runoff	-15% reservoir yield	Sensitivity scenario in 2100 selected from TAR and AR4 GCMs with good skill. + 15% PET, -10% Precip			Krol *et al*. (2011)
North SA	Essequibo (Guyana)	Runoff	-50%	2050s	HadCM3	A2	Palmer *et al*. (2008)
	Magdalena (Colombia)	Runoff	Not significant changes in near future. End of 21st not consistent trend but changes in seasonality.	2015–2035 and 2075–2099	CMIP3 multi-model ensemble (MME)	A1b	Nakaegawa and Vergara (2010)
	Sinu (Colombia)	Runoff	-2 to -35%	2010-2039	CCSRNIES, CSIROMK2B, CGCM2, HadCM3 (different runs of these models)	A2	Ospina-Noreña *et al*.(2009a; 2009b)
CA	Lempa	Runoff	Statistically significant reduction in the order of 13% (B1) and 24% (A2).	2000-2100 (results presented for 2070-2100)	CMIP3	A2, B1	Maurer *et al*. (2009)

	Grande de Matagalpa	Runoff	-70%	2050s	HadCM3	A2	Palmer *et al*. (2008)
	Mesoamerica (6.5-22 N and 76.5-99 W)	Runoff	Decrease across the region (different magnitudes and uncertainty associated) even in areas where precipitation increases	2070-2100	CMIP3	A2, A1b, B1	Imbach *et al*. (2012)

Table 27-5: Impacts on agriculture.

Country/ Region	Activity	Time slice	SRES	CO_2	Changes	Source
Uruguay (SESA)	Annual crops	2030/2050/2070/2100	A2		+185/-194/-284/-508	ECLAC (2010d)
		2030/2050	B2		+92/+169	
	Livestock	2030/2050/2070/2100	A2		+174/-80/-160/-287	
		2030/2050	B2		+136/+182	
	Forestry	2030/2050/2070/2100	A2		+15/+39/+52/+19	
		2030/2050/2070	B2		+6/+13/+18	
Paraguay (SESA)	Cassava	2020/2050/2080	A2		+16/+22/+22	ECLAC (2010d)
	Wheat	2020/2050/2080	A2		+4/-9/-13	
			B2		-1/+1/-5	
	Maize	2020/2050/2080	A2		+3/+3/+8	
			B2		+3/+1/+6 A2	
	Soybean	2020/2050/2080	A2		0/-10/-15	
			B2		0/-15/-2	
	Bean	2020/2050/2080	A2		-1/+10/+16	
Argentina (SESA)	Maize	2080	A2/B2	N	-24/-15	ECLAC (2010d)
			A2/B2	Y	+1/0	
	Soybean	2080	A2/B2	N	-25/-14	
			A2/B2	Y	+14/+19	
	Wheat	2080	A2/B2	N	-16/-11	
			A2/B2	Y	+3/+3	
	Soybean	2020/2050/2080	A2	Y	+24/+42/+48	Travasso et al. (2008) AIACC
			B2	Y	+14/+30/+33	
	Maize	2020/2050/2080	A2	Y	+8/+11/+16	
			B2	Y	+5/+5/+9	
Brazil (SESA)	Rice		$2CO_2$/0ºC	Y	+60	Walter *et al*. (2010)
			$2CO_2$/+5ºC	Y	+30	
	Bean	2050-2080	A2	N	Up to -30%	Costa *et al*. (2009) (*1)
		2020-2050-2080	A2+CO_2	Y	Up to: +30/+30/+45	
		2020-2050-2080	A2+CO_2+T	Y	Up to: +45/+75/+90	
	Maize	2050-2080	A2	N	Up to -30%	
		2050-2080	A2+CO_2	Y	Near to -15%	
		2020-2050-2080	A2+CO_2+T	Y	Up to: +40/+60/+90	
	Arabica coffee (*2)		0 to +1ºC		+1.5%	Zullo *et al*. (2011)
			+1 to +2ºC		+15.9%	
			+2 to +3ºC		+28.6%	
			+3 to +4ºC		-12.9%	
Brazil Sao Pablo	Sugarcane	2040	Pessimistic		+6%	Marin *et al*. (2009)
		2040	Optimistic		+2%	
Brazil Northeast	Cassava	2030		N	0 to -10	Lobell *et al*. (2008)
	Maize	2030		N	0 to -10	
	Rice	2030		N	-1 to -10	
	Wheat	2030		N	-1 to -14	
	Maize				-20 to -30	Margulis *et al*. (2010)
	Bean				-20 to -30	
	Rice				-20 to -30	
	Cowpea bean (*2)		+1.5ºC		-26%	Silva *et al*. (2010)
			+3.0ºC		-44%	
			+5.0ºC		-63%	
Central America (CA)	Maize		A2		0/0/-10/-30	ECLAC (2010d)
	Bean	2030/2050/2070/2100	A2		-4/-19/-29/-87	
	Rice		A2		+3/-3/-14/-63	
	Rice	2020-2040		N	0 to -10	Lobell *et al*. (2008)
	Wheat	2020-2040		N	-1 to -9	
Panamá	Maize	2020-2050-2080	A2	Y	-0.5/+2.4/+4.5	Ruane et al. (2011)
		2020-2050-2080	B1	Y	-0.1/-0.8/+1.5	
Andean Region	Wheat	2020-2040		N	-14 to +2	Lobell *et al*. (2008))
	Barley			N	-1 to -8	

	Potato Maize			N N	0 to -5 0 to -14	
Colombia	All main crops	2050	17GCM-A2		80% of crops impacted in more than 60% of current cultivated areas	Ramirez *et al*. (2012)
Chile 34.6ºS/38.5ºS	Maize Wheat	2050 2050	A1FI A1FI	Y Y	-5% to -10% -10% to -20%	Meza and Silva (2009)

N: Without considering CO2 biological effects; Y: Considering CO2 biological effects

(*1) Huge spatial variability, the values are approximated

(*2) Changes in the percentage of areas with low climate risk

Table 27-6: Comparison of consumption of different energetics in Latin America and the world (in thousand tonnes of oil equivalent (ktoe) on a net calorific value basis).

Energy resource		LATAM						World					
		TFC (non electricity)		TFC (via electricity generation)		Total TFC		TFC (non electricity)		TFC (via electricity generation)		TFC	
Fossil	Coal and Peat	9,008	3%	1,398	2%	10,406	3%	831,897	12%	581,248	40%	1,413,145	17%
	Oil	189,313	55%	8,685	13%	197,998	48%	3,462,133	52%	73,552	5%	3,535,685	44%
	Natural Gas	59,44	17%	9,423	14%	68,863	17%	1,265,862	19%	307,956	21%	1,573,818	19%
Nuclear	Nuclear	0	0%	1,449	2%	1,449	0%	0	0%	193,075	13%	193,075	2%
Renewable	Biofuels and waste	82,997	24%	2,179	3%	85,176	21%	1,080,039	16%	20,63	1%	1,100,669	14%
	Hydro	0	0%	45,92	66%	45,92	11%	0	0%	238,313	17%	238,313	3%
	Geothermal, solar, wind, other renewable	408	0%	364	1%	772	0%	18,265	0%	26,592	2%	44,857	1%
TOTAL		341,166	100%	69,418	100%	410,584	100%	6,658,196	100%	1,441,366	100%	8,099,562	100%

* TFC: Total final consumption

Source: IEA, 2012

Table 27-7: Overview on local, regional, national and international adaptation programs, projects and initiatives relevant for the region.

Countries	Name of Project/ Case Study/ Business Case	Specification of Approach/ Strategy/ Adaptation Area	Platform- NWP (PSI;LCS;EbA;AP)/ weAdapt	Details on platform specification*
Argentina	Adaptation strategies for the Jujuy model forest in NW Argentina	Adaptation efforts in a forest model in Argentina	weAdapt	n.a.
Belize	Adapting to climate change in the Mesoamerican Reef	Assessment of vulnerability; Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Marine and coastal (WWF)
Belize	Ecosystems, Development and Climate Adaptation: Improving the base for policies, planning and management	Mainstreaming EbA in Belize	weAdapt	n.a.
Bolivia	Qhuthañas in Bolivia Collecting and storing rainwater in small dams (qhuthañas)	Rainwater harvesting	NWP- LCS	Hazards: Drought, aridity/ Impacts: Loss of crops; Water shortage
Bolivia	Enhancing adaptive capacity in semi-arid mountainous regions, Bolivia	Assessment of vulnerability; Improvement in capacity design and policy measures; Implementation of EBA measures	NWP- EbA	Mountain; Forest and woodland (The Netherlands Climate Assistance Programme (NCAP))
Bolivia	Building Capacity in Vulnerable Mountain Regions	Water Scarcity in Mountain Regions	weAdapt	n.a.
Bolivia	Climate Change Adaptation in Practice; Rescuing the Past: Using Indigenous Knowledge to Adapt to Climate Change in Bolivia	Using Indigenous Knowledge to Adapt to Climate Change in Bolivia	weAdapt	n.a.
Bolivia	Understanding Adaptation and Mitigation Strategies of Andean People - Bolivia	INCA- Bolivia	weAdapt	n.a.
Bolivia	Adaptation strategies for the Chiquitano tropical dry forest in Eastern Bolivia	Adaptation efforts in the tropical dry forest of Bolivia	weAdapt	n.a.
Bolivia	Ecosystem-based strategies and innovations in water governance networks for adaptation to climate change in Latin American Landscapes	EcoAdapt	weAdapt	n.a.
Brazil	New technologies for climate change adaptation	Food security, agriculture, forestry and fisheries	NWP- PSI	Chemicals (BASF)
Brazil	Insuring against climate impacts and rewarding sustainable business practices	Business	NWP- PSI	Financial Services (Allianz)
Brazil	Disaster preparedness, local capacity building, and planning	Science, assessment, monitoring and early warning; Education and training	NWP- PSI	Consulting and Environmental Services (Riverside Technology)

Brazil	New insurance products and climate risk	Business; Transport, infrastructure and human settlements	NWP- PSI	Financial Services (HSBC)
Brazil	Community Reforestation in Rio de Janeiro, Brazil; Preventing soil erosion and landslides	Soil conservation; Natural resource management	NWP- LCS	Hazard: Floods/ Impact: Soil erosion
Brazil	Babassu Palms in Brazil Harvesting the fruits for oil and protein	Diet diversification	NWP- LCS	Hazards: Drought, aridity/ Impacts: Loss of crops
Brazil	Tires walls in Rio de Janeiro, Brazil Building retaining walls from crape tires	Soil conservation	NWP- LCS	Hazard: Floods/ Impact: Soil erosion
Brazil	Rio de Janeiro's Community Reforestation Project	Improvement in capacity; design and policy measures; Implementation of EBA measurres	NWP- EbA	Urban; Forest and woodland (City of Rio)
Brazil	Ecosystem-Based Adaptation in Marine, Terrestrial and Coastal Regions as a Means of Improving Livelihoods and Conserving Biodiversity in the Face of Climate Change	Assessment of vulnerability; Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Marine and coastal; forest and woodland; agriculture; inland water (Federal Environment Ministry of Germany, Conservation International Foundation)
Brazil	Adaptive management of pirarucu (Arapaima gigas)	Adaptive management	weAdapt	n.a.
Brazil	Promotion of drought resistant native fruits	Resistance to droughts	weAdapt	n.a.
Chile	SMCE/NAIADE: Evaluating the effects of the Alumysa Project in the Aysen Region in Chile	Adaptation tools, case study SMCE/NAIADE	weAdapt	n.a.
Chile	Adaptation strategies for the Alto Malleco model forest in Chile	Adaptation efforts in a forest model in Chile	weAdapt	n.a.
Colombia	Adaptation program to support ecosystem services	Water resources	NWP- PSI	Water Management (EEAB-Bogotá Water and Sewage Company)
Colombia	Integrated National Adaptation Plan - Colombia highland ecosystems	Assessment of vulnerability; Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Mountain; Inland Water (GEF; World Bank; Conservation International)
Colombia	Orito Ingi Ande Medicinal Plants Sanctuary	Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Forest and woodland (Government of Colombia; local communities)
Colombia	Implementing Climate Adaptation Strategies in the World's Most Outstanding Natural Places	Delivering Adaptation	weAdapt	n.a.
Colombia	Building Capacity in the Colombian coastal area	Integrated Coastal Management for Adaptation	weAdapt	n.a.

Colombia, El Salvador, Nicaragua	Integrating Climate Change Risks and Opportunities into National Development Processes and United Nations Country Programming (UNDP)	not specified	NWP- AP	Academic, Governmental, Intergovernmental
Costa Rica	Flood preparedness in Costa Rica Implementing a community training programme	Disaster risk management	NWP- LCS	Hazard: Floods/ Impact: Damage to human settlements
Costa Rica	Hurricane-resistant housing in Costa Rica Constructing low-cost reinforced bamboo houses	Improved housing design	NWP- LCS	Hazard: Storms/ Impact: Damage to human settlements
Ecuador	Providing farming training and assistance	Education and training; Food security, agriculture, forestry and fisheries; Water resources	NWP- PSI	Food and Beverages (Nestlé)
Ecuador	Flood-Resistant Housing in Ecuador Constructing elevated bamboo houses	Improved housing design	NWP- LCS	Hazard: Floods/ Impact: Damage to human settlements
Ecuador and Peru	The CEIBA-PILARES project	Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Forest and woodland (Nature and Culture International)
El Salvador	Vulnerability and Capacity Analysis of Communities Amando López and Octavio Ortiz in the Lower Lempa Valley	Vulnerability and Capacity Analysis of Communities in El Salvador	weAdapt	n.a.
El Salvador, Costa Rica, Panama	Climate Change Governance Capacity: Building Regionally and Nationally Tailored Ecosystem-Based Adaptation in Mesoamerica	Assessment of vulnerability; Improvement in capacity design and policy measures; Implementation of EBA measures	NWP- EbA	Marine and coastal; Agriculture; Inland waters (Federal Environment Ministry of Germany, International Union for Conservation of Nature)
El Salvador; Guatemala; Nicaragua	Coffee Under Pressure: Climate Change and Adaptation in Mesoamerica (CUP)	Food security, agriculture, forestry and fisheries	NWP- PSI	Food and Beverages; Agriculture (Green Mountain Coffee Roasters (GMCR); International Center for Tropical Agriculture (CIAT); Catholic Relief Services (CRS))
El-Salvador	Drought-resistant agriculture in El-Salvador	Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Agriculture (Red Cross; World Food Programme)
Guatemala	Finding Points of Engagement to Integrate Climate Change Adaptation into Water Management Planning	Integrating Climate Adaptation into National Policy (NCAP)	weAdapt	n.a.
Guyana	Participatory school and community-based disaster preparedness	Community-based disaster preparedness	weAdapt	n.a.
Honduras	FORCC: Using forests to enhance resilience to climate change	FORCC Honduras	weAdapt	n.a.
Nicaragua	Reduction of risks and vulnerability from floods and droughts in the Estero Real	Adaptation fund: reducing floods and droughts	weAdapt	n.a.

	watershed			
Nicaragua, Guatemala, El Salvador	Using the Maya Nut Tree to increase tropical agroecosystem resilience to climate change in Central America and Mexico	Improvement in capacity, design and policy measures; Implementation of EBA measures	NWP- EbA	Forest and woodland; Agriculture (Maya Nut Institute)
Peru	Adaptation for Smallholders to Climate Change (AdapCC)	Food security, agriculture, forestry and fisheries	NWP- PSI	Food and Beverages (Cafédirect; GIZ)
Peru	Waru Waru in Peru; Utilizing an ancient irrigation and drainage system	Sustainable water management	NWP- LCS	Hazards: Drought, aridity; Floods/ Impact: Loss of crops
Peru	Understanding Adaptation and Mitigation Strategies of Andean People - Peru	INCA- Peru	weAdapt	n.a.
Peru	Response to impacts of glacial retreats	Response to impacts of glacial retreats	weAdapt	n.a.
Suriname	Sustainable Livelihoods in the Coastal Zone of Suriname	Local Adaptation in Coasts	weAdapt	n.a.
Central America	Hurricane guarantees and waivers	Tourism	NWP- PSI	Tourism and Recreation (Apple Vacations; Club Med; Sandals; SuperClubs; TNT Vacations)
Multiple	Provision of solar energy builds resilience of rural population	Renewable energy systems	NWP- PSI	Energy and Utilities (HiNation AB)
Multiple	SkyHydrant Water Purification Technology	Water resources	NWP- PSI	Science and Technology (Siemens)
Multiple	Adapting to Climate Changes for Potato Production in The Andes	Water resources	NWP- PSI	Food and Beverages (PepsiCo South America, Caribbean and Central America Foods)
Multiple	Product solutions for a future of more constrained resources	Water resources	NWP- PSI	Consumer Packaged Goods (Unilever)
Multiple	Boosting crop yield for every drop of water	Capacity building, education and training; Finance and insurance; Food, agriculture, forestry and fisheries; Technology and Information &Communications Technology (ICT); Water resources	NWP- PSI	Agriculture (Syngenta)
Multiple	The Latin American Water Funds Partnership	Capacity building, education and training; Finance and insurance; Science, assessment, monitoring and early warning; Water resources	NWP- PSI	Food and Beverages (Femsa Foundation)
not specified	Partners for Resilience	Capacity building; Communication and awareness raising; Knowledge management	NWP- AP	Non-Governmental
not specified	Assessment of Impacts and Adaptations to Climate Change in Multiple Regions and Sectors (AICCC)	Education; communication and awareness raising; financial support	NWP- AP	Intergovernmental

not specified	BASIC project	Education; communication and awareness raising; knowledge management	NWP- AP	Academic
not specified	Iberoamerican Network of Climate Change Bureaus (RIOCC)	Knowledge management, education; training	NWP- AP	Intergovernmental
not specified	Inter-American Development Bank Activities (IDB)	Financial support	NWP- AP	Intergovernmental
not specified	Oficina de Riesgo Agropecuario (ORA) - República Argentina Activities	Education	NWP- AP	Governmental
not specified	Practical Action Activities	Pilot adaptation programmes/projects	NWP- AP	Non-Governmental
not specified	ProVentium Consortium Activities	Education, training; knowledge management	NWP- AP	Non-Governmental
not specified	The Netherlands Climate Assistance Programme	Communication and awareness raising; training; education	NWP- AP	Non-Governmental
not specified	Water Center for the Humid Tropics of Latin America and the Caribbean Activities (CATHALAC)	Communication and awareness raising; training; education	NWP- AP	Academic

* Details are provided for NWP platforms and comprehend for PSI, business sector/ company; for LCS, hazard/impact; for EbA, ES/ implementing institution; and for AP, the type of organization (see also NWP interface, UNFCCC, 2012xx).

Source: Authors based on UNFCCC (2012b) and weAdapt (2012)

Table 27-8: Cases of government-funded PES schemes in CA and SA.

Countries	Level	Start	Name	Benefits	References
Brazil	Sub-national (Amazonas state)	2007	*Bolsa Floresta*	By 2008, 2700 traditional and indigenous families already benefitted: financial compensation and health assistance in exchange for zero deforestation in primary forests.	Viana (2008)
Costa Rica	National	1997	FONAFIFO fund	PES is a strong incentive for reforestation and, for agroforestry ecosystems alone, over 7,000 contracts have been set since 2003, and nearly 2 million trees were planted.	Montagnini and Finney (2011)
Ecuador	National	2008	*Socio-Bosque*	By 2010, the program already included more than half a million hectares of natural ecosystems protected and has over 60,000 beneficiaries.	De Koning *et al*. (2011)
Guatemala	National	1997	Programa de Incentivos Forestales, PINFOR	By 2009, the program included 4,174 beneficiaries who planted 94,151 hectares of forest. In addition, 155,790 hectares of natural forest were under protection with monetary incentives.	Instituto Nacional de Estadística (2011)

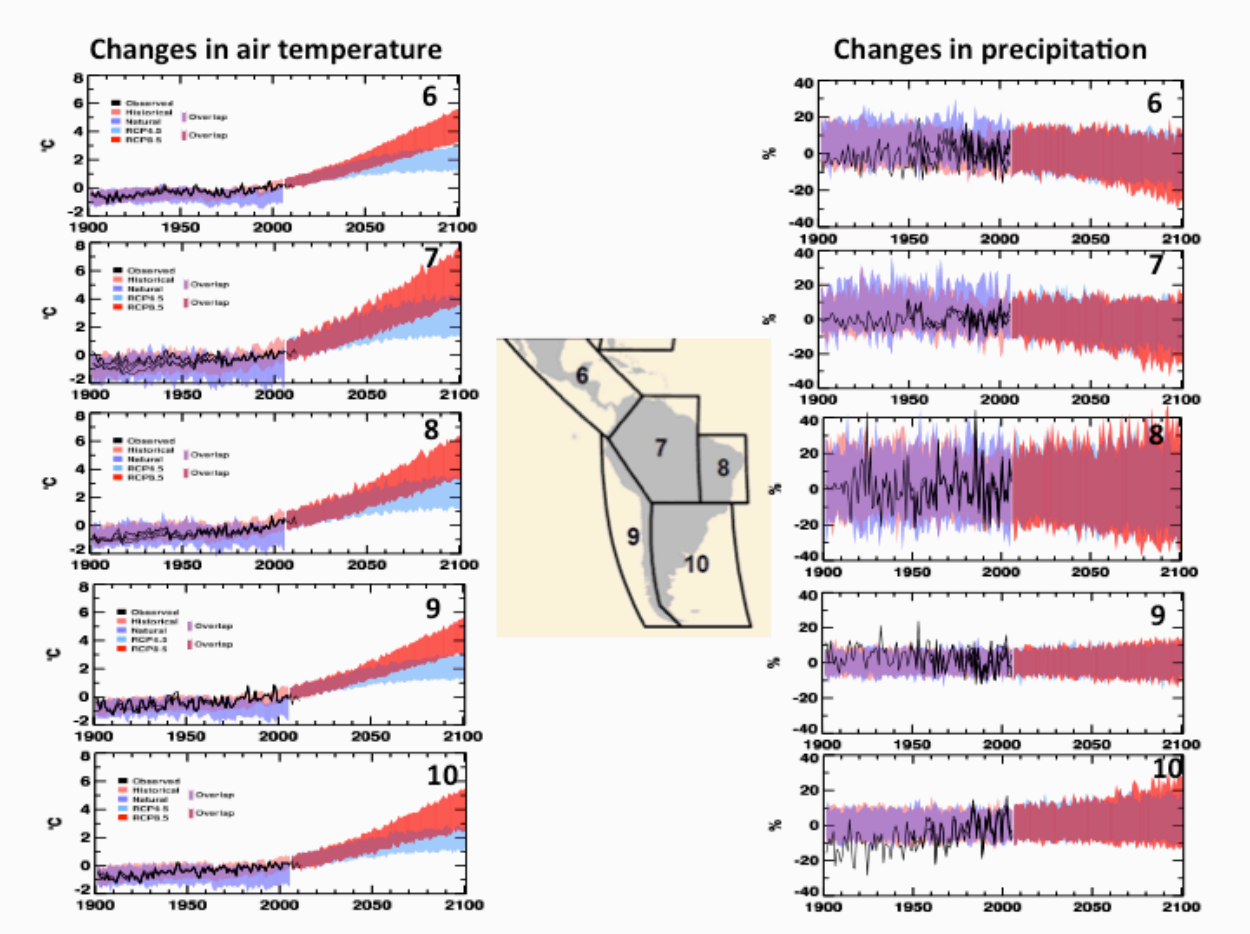

Figure 27-1: Observed and simulated variations in past and projected future annual average temperature over land areas of the Central and South American "SREX regions". Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30), the "RCP4.5" emissions scenario (68), and the "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.

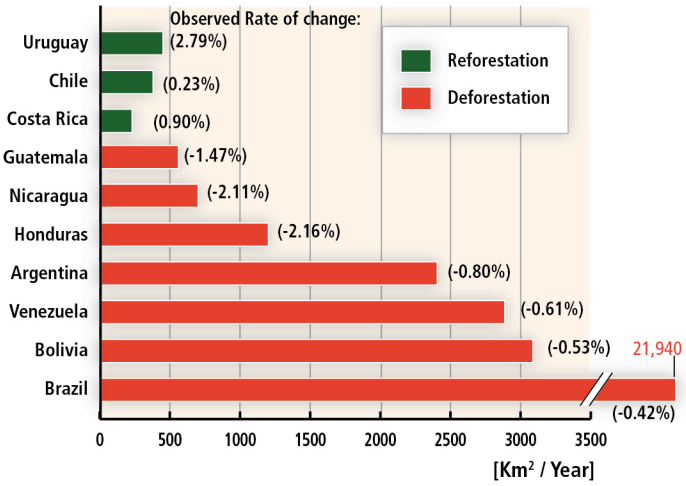

Figure 27-2: Area deforested per year for selected countries in CA and SA (2005-2010). Notice three countries listed with a positive change in forest cover (based on data from FAO, 2010).

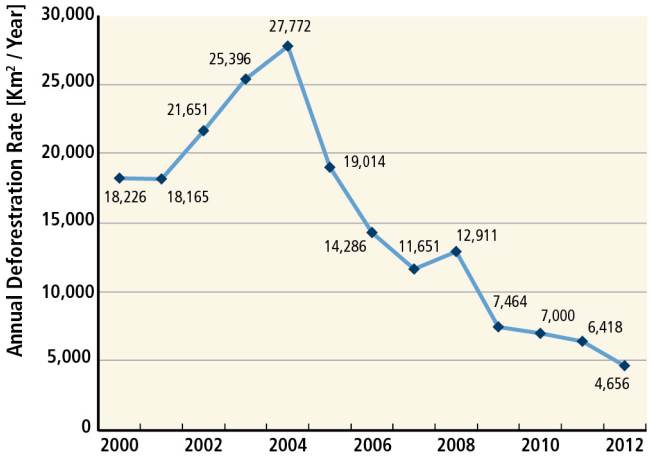

Figure 27-3: Deforestation rates in the Brazilian Amazonia (km²/year) based on measurements by the PRODES INPE project (see also INPE, 2011).

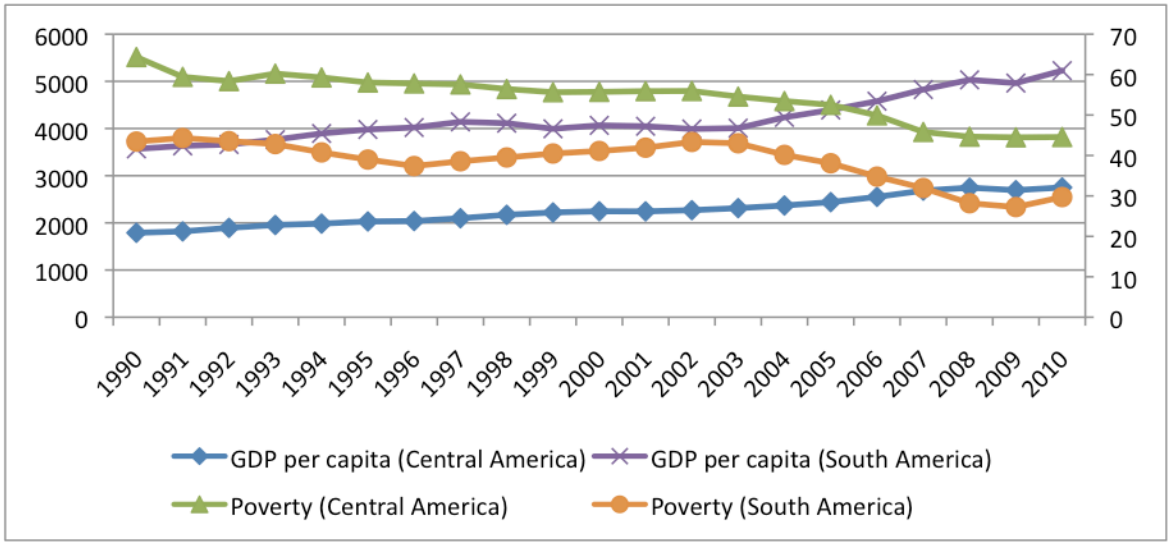

Figure 27-4: Evolution of GDP per capita and poverty from 1990-2011: CA and SA (US-Dollars per inhabitant at 2005 prices and percentages) (ECLAC on the basis of CEPALSTAT (2012) and ECLAC (2011))

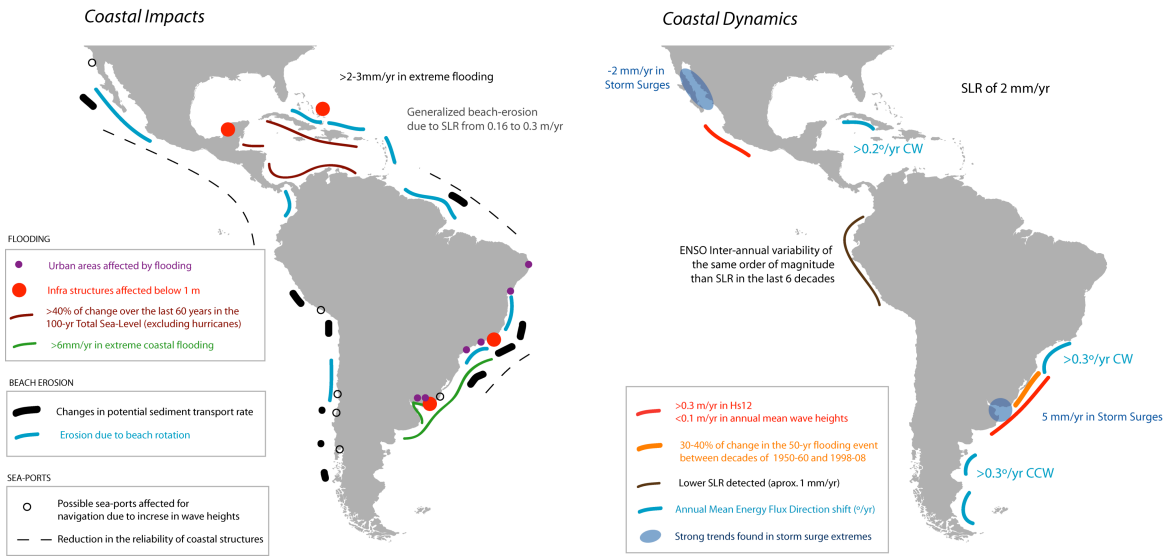

Figure 27-5: Current and predicted coastal impacts and coastal dynamics in response to climate change (elaborated by Iñigo Losada, ECLAC)

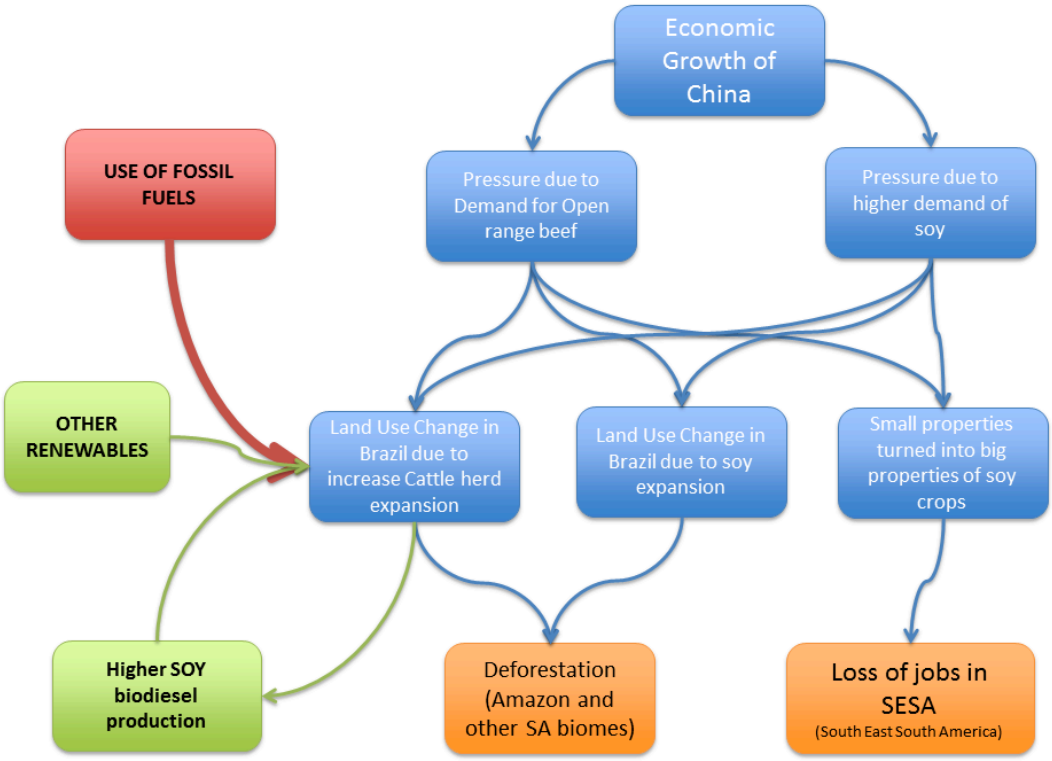

Figure 27-6: Soy teleconnections and major effects in SA. Economic growth giant consumers as China pressurize the soy production system in SA, increasing the production of biodiesel, but demanding more energy in general. (partly based on Nepstad and Stickler (2008), and Tomei and Upham (2009))

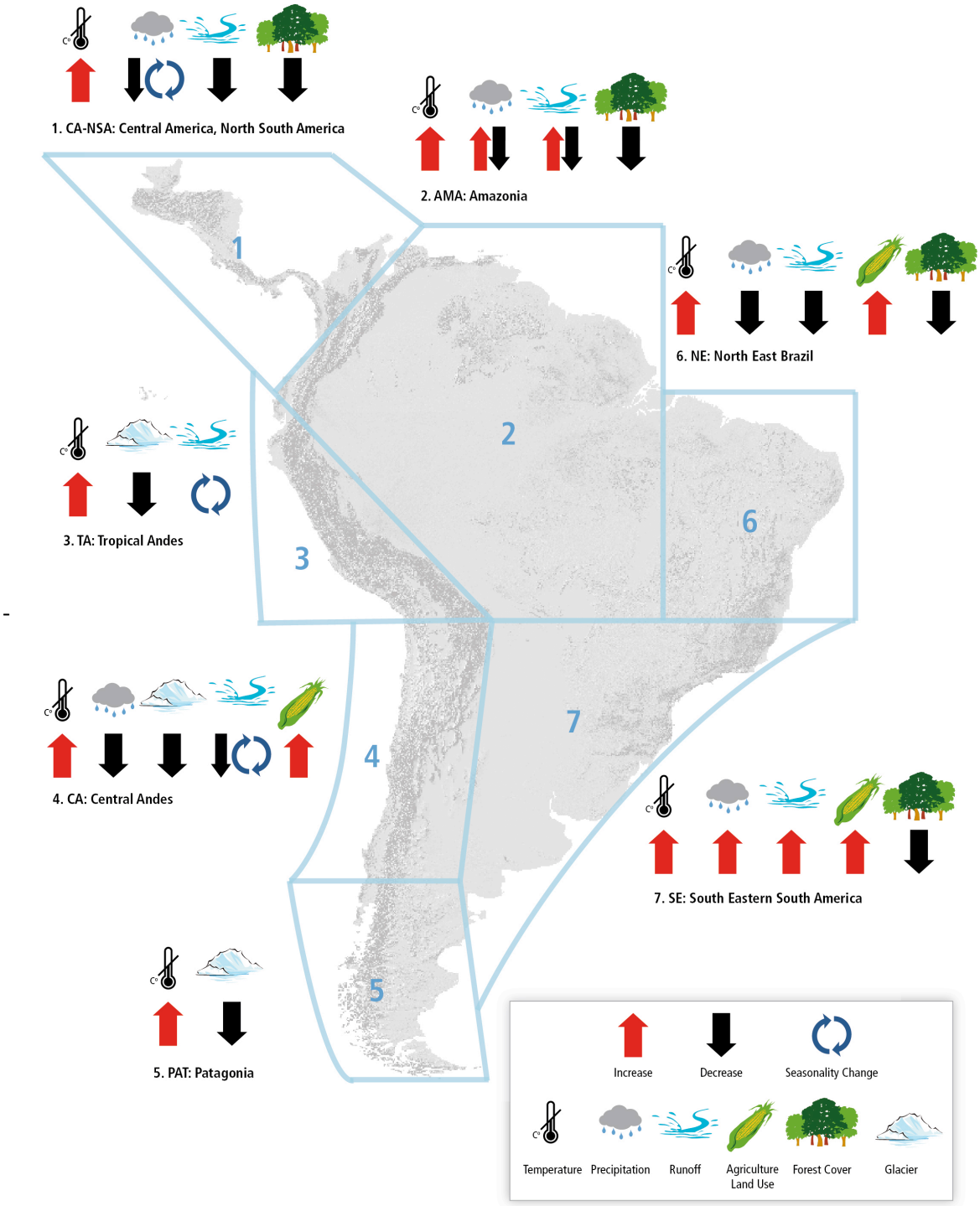

Figure 27-7: Summary of observed changes in climate and other environmental factors in representative regions of CA and SA. The boundaries of the regions in the map are conceptual (not precise geographic nor political) and follow those developed in Figure 3-1 of the IPCC SREX (IPCC, 2012). Information and references to changes provided are presented in different sections of the chapter.

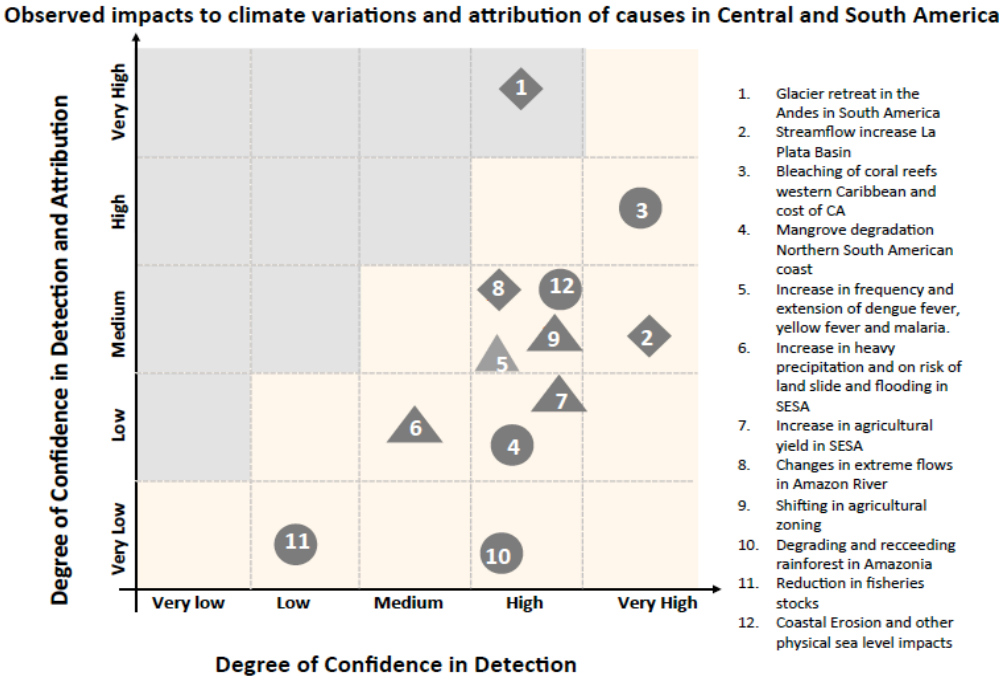

Figure 27-8: Observed impacts of climate variations and attribution of causes in CA and SA.

Chapter 28. Polar Regions

Coordinating Lead Authors
Oleg A. Anisimov (Russian Federation), Joan Nymand Larsen (Iceland)

Lead Authors
Andrew Constable (Australia), Anne Hollowed (USA), Nancy Maynard (USA), Pål Prestrud (Norway), Terry Prowse (Canada), John Stone (Canada)

Contributing Authors
Terry Callaghan (UK), Mark Carey (USA), Peter Convey (UK), Andrew Derocher (Canada), Bruce C. Forbes (Finland), Solveig Glomsrød (Norway), Dominic Hodgson (UK), Eileen Hofmann (USA), Grete K. Hovelsrud (Norway), Gita L Ljubicic (Canada), Harald Loeng (Norway), Eugene Murphy (UK), Steve Nicol (Australia), Anders Oskal (Norway), Phil Trathan (UK), Barbara Weinecke (Australia), Fred Wrona (Canada)

Review Editors
Maria Ananicheva (Russian Federation), Terry Chapin (USA)

Volunteer Chapter Scientist
Vasiliy Kokorev (Russian Federation)

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Executive Summary

The physical, biological and socio-economic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by factors other than climate change but also demography, culture and economic development. There is evidence that climate change has compounded some of the existing vulnerabilities caused by these other factors (*high confidence*). [28.2.5, 28.4]

The rate rather than the magnitude of changes in the polar regions may become more of a key factor leading to dramatic impacts on natural and social systems if it exceeds the rate at which systems can adapt (*low to medium confidence*). [28.4.2] The decline of Arctic sea-ice in summer is occurring at a rate that exceeds most model projections (*high confidence*). Evidence of similarly rapid rates of change is emerging in some regions of Antarctica, particularly the ice shelves. There is some evidence, for example in the reduction of sea-ice extent in the Arctic and in the west Antarctic Peninsula that the changes are non-linear, and may be accelerating. [IPCC AR5 WGI Chapter 14]

The primary conservation concern for polar bears over the foreseeable future or three generations is the recent and projected loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent.

Environmental changes and ecosystem responses in the marine environment differ between ecological regions within both the Antarctic and Arctic, largely as a result of differences in the changes to sea ice dynamics and sea surface temperature (*high confidence*). [28.2.2] The changing sea ice environments off the Western Antarctic Peninsula and in the Arctic have resulted in measurable changes in phytoplankton communities. In the Western Antarctic Peninsula region, krill production has been linked to sea ice extent and duration. Further sea ice changes are likely to have a negative effect on krill populations and on the species that depend on them (*high confidence*). [28.2.2.2]

Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the Polar Regions. Responses will vary depending on the vulnerability of species to changing ocean conditions. Some marine species have shifted their spatial distribution in response to changing environmental conditions. The response rate and the spatial extent of range shifts will differ by species based on their vulnerability to change and their life history. [28.2.2; 28.3.2] Penguins and flying birds restricted to sub-Antarctic islands will have lower reproductive success because of the added cost of obtaining prey further to the south (*medium confidence*).

Loss of sea ice in summer is expected to enhance secondary pelagic production in the Arctic with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). These changes are expected to alter the species composition and carrying capacity of pelagic and benthic marine habitats with associated impacts on the ability of the region to support marine fish and shellfish populations (*medium confidence*). [28.2.2.1]

Shifts in the timing of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival (*medium confidence*). The breeding cycle of some shellfish and fish in the Arctic coincides with the spring bloom of ice algae and ocean phytoplankton and subsequent secondary production which is considered to enhance survival of the larvae. If the timing between peaks in primary production and secondary production are no longer matched to the timing of spawning or egg release, survival could be impacted with cascading implications to higher trophic level consumers. Higher predators have highly synchronized breeding phenologies in Polar Regions, requiring prey to be available near to land-based colonies at certain times of the year. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). [28.2.2, 28.3.2] Mismatch between the phenology of different trophic levels caused by climate change has also been suggested to be a potential problem for Arctic terrestrial mammals and birds [28.2.3.5], but the scientific documentation for this is weak.

Ocean acidification has the potential to inhibit egg development and shell formation of some zooplankton and krill in the polar regions with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Eggs and larvae of Antarctic krill have been shown to be vulnerable to increased concentrations of CO_2 in the water (*high confidence*). As well, there is increasing evidence that pelagic mollusks (pteropods) are vulnerable to ocean acidification (*medium confidence*). If these effects result in widespread impacts on populations then they will be far reaching on regional foodwebs. [28.2.2, 28.3.2]

Future trends in populations of Antarctic marine mammals and birds will be a complex response to multiple stressors and indirect effects (*high confidence*). [28.3.2.2] Changes in populations of many Antarctic predators are well documented [28.2.2.2]. Some species, such as Antarctic fur seals and humpback whales, are increasing as they recover from past exploitation (*very high confidence*). Decreases in populations of other species (chinstrap and Adelie penguins on the Western Antarctic Peninsula) and Emperor penguins generally have been associated with long-term physical changes such as sea ice (*medium confidence*). [28.2.2.2]

Climate change is impacting terrestrial and freshwater ecosystems in some areas of the Antarctica and Arctic. This is due to ecological effects resulting from reductions in the duration and extent of ice cover and enhanced permafrost thaw (*very high confidence*), and through changes in the precipitation-evaporation balance (*medium confidence*). [28.2]

The primary conservation concern for polar bears over the foreseeable future or three generations is the recent and projected loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent.

The abundance and biomass of deciduous shrubs and grasses has increased substantially over large – but not all – parts of the Arctic tundra in recent years (*very high confidence)*. It is *very likely* that most of this increase in biomass can be attributed to longer growing seasons and higher summer temperatures.

The tree line has moved northwards and upwards in many, but not all, Arctic areas and significant increases in tall shrubs have been observed in many places (*high confidence)*. Other factors such as changes in herbivore grazing, anthropogenic disturbances and changes in precipitation and the snow/water regime also influence the tree line and structural vegetation changes in the northern boreal forest. [28.2.3.2, 28.2.3.3]

Increased energy availability (warming) in combination with increased water availability is expected to lead to increased productivity, biomass and the development of community complexity in native Antarctic terrestrial biota (*high confidence*). However, these responses are potentially confounded by multiple stressors, including human activities (research stations, tourism etc). [28.3.3.2] Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous taxa, the majority likely to arrive through direct human assistance, which poses the greatest threat to terrestrial plant and animal communities in the future (*high confidence*). [28.3.3.4]

Summer phytoplankton levels in many Antarctic lakes have increased significantly together with higher nutrient inputs from exposed fell field soils and thawed ground (*very high confidence*). [28.2.1.2] These lakes have experienced extended open-water periods allowing the water and sediments to absorb more solar energy which has further increased lake water temperature during winter. Lakes with a low lake depth to surface area ratio have been susceptible to inter-annual and inter-decadal variability in the water balance (*high confidence*).

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase – especially for many indigenous peoples (*high confidence*). [28.2.4] Impacts include injury and risk from extreme and unpredictable weather including flooding, changing in ice and snow conditions endangering hunting, herding, and fishing; food insecurity and malnutrition due to decreased access to local foods and loss or compromised freshwater sources; permafrost and erosion damage to homes and infrastructure and loss of homelands as well as increased social and economic problems due to loss of traditional livelihood, language, culture and relocation of communities. These impacts are expected to vary among the diverse settlements that range from small, remote predominantly indigenous to large industrial settlements (*high confidence*). Many of these impacts are often related to the fact that a large percentage of northern settlements are along coastlines or beside rivers and lakes.

Food security of many indigenous and rural residents in the Arctic is being impacted by climate change, and when seen in combination with the effects of globalization and resource development these impacts are projected to increase significantly in the future (*high confidence*). [28.2.7.1, 28.2.4] There have been noticeable impacts on the livelihoods of indigenous peoples' ways of life particularly their access to traditional foods that have provided sustenance, cultural, religious, economic, and community well-being for many generations. However, Arctic indigenous people have a high adaptive capacity and have begun to develop novel solutions to adapt to climate changes, such as combining traditional and scientific knowledge and co-producing climate studies with scientific partners. [28.2.7.1, 28.2.7.2, 28.4.1]

Climatic and other large-scale changes can have potentially large effects on Arctic communities where relatively small and narrowly based economies leave a narrower range of adaptive choices. [28.2.6.1.5] Formal and market-based economic activity is projected to have both costs and benefits, with some commercial activities becoming more profitable while others will face decline. Increased economic opportunities along with challenges for culture, security and environment, are expected with the increased navigability of Arctic marine waters and the expansion of land- and fresh water-based transportation networks (*high confidence*). [28.2.6.1.4, 28.4.2]

Significant impacts on the availability of key subsistence marine and terrestrial species are projected as climate continues to change with the ability to maintain economic livelihoods being affected. The informal, subsistence-based economy will be impacted by changing climate (*high confidence*). Indigenous hunters, whalers, walrus hunters and herders are reporting non-predictable conditions resulting from more frequent occurrence of

unusual weather events. There *is high confidence* that changing sea-ice conditions will result in more difficult access for hunting marine mammals and greater risk for the long-term viability of polar bear populations. [28.2.6.1.7]

Rising temperatures, leading to the further thawing of permafrost, and changing precipitation patterns have the potential to affect all infrastructure types and related services in the Arctic (*high confidence*). Much of the infrastructure is dependent upon the frozen soil to provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines and provide access to remote communities in the winter. [28.2.6.5.1]

Although there is general agreement that both indigenous and non-indigenous people in the Arctic have a long history of adapting to change, the complex inter-linkages between societal, economic, political factors and climatic stresses represent unprecedented challenges for northern communities (*high confidence*). [28.4]

28.1. Introduction

Previous IPCC reports define the Arctic as the area within the Arctic Circle (66ºN), and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58ºS (IPCC, 2001). For the purpose of this report we use the conventional IPCC definitions as a basis, while incorporating a degree of flexibility when describing the Polar Regions in relation to particular subjects, similarly to the approaches adopted in the Arctic Climate Impact Assessment (ACIA) and Antarctic Climate Change and the Environment (ACCE) report (ACIA 2005, Convey et al. 2009; Turner *et al*., 2009; Convey *et al*., 2009). Changes in the physical climate regime in the Polar Regions are addressed in detail in IPCC WG-1 report.

[INSERT FIGURE 28-1 HERE
Figure 28-1: Location maps of the North and South polar regions. Source: IPCC, 2007. [Note: WGII AR4 Figure 15.1 to be updated, including the addition of major currents. Credit: P. Fretwell, British Antarctic Survey.]]

Summary of Knowledge Assessed in other Reports (including IPCC, SWIPA, IPY etc.)

Several recent international climate assessments, including the IPCC (2007), the synthesis report on Snow, Water, Ice and Permafrost in the Arctic (SWIPA, 2011), the State of the Arctic Coast 2010 (2011) reports, the Antarctic Climate and the Environment (Turner *et al*., 2009), and reports summarizing the findings of the International Polar Year (IPY) draw a consistent pattern of climatic and environmental changes in the Polar regions, as well as climate-driven societal and economical changes in the Arctic in the beginning of the 21st century. Here we summarize the key findings of these assessments focusing on impacts of climate change and briefly addressing the relevant information about changes in the physical climate parameters, which are detailed in the report of the Working Group 1 to the Fifth IPCC assessment.

Arctic

In the past few decades Arctic was characterized by the highest regional rates of changes in selected parameters of the physical climate regime. Such changes are essential for understanding a cascade of the environmental and societal impacts addressed in this chapter. Since 1980 Arctic has been warming at approximately twice the global rate demonstrating the strongest temperature changes (~ 1 °C/decade) in winter and spring, and smallest in autumn (IPCC WG2 2007, SWIPA 2011). Sea ice declined at an unprecedented rate in all seasons reaching the absolute minimum of 3.41 million km^2 in September 2012, which is 18% lower than in 2007, when the previous record of 4.17 million km^2 was recorded. (IPCC WG1 2014; Arctic report card, 2012). The Arctic Ocean is projected to become nearly ice-free in summer within this century, while some models suggest it may happen within the next thirty to forty years (IPCC WG1 Fifth AR). According to SWIPA (2011), the duration of snow cover extent and snow depth are decreasing in North-America while increasing in Eurasia. Since late 1970s permafrost temperatures have increased typically between 0.5 to 2 °C, with warming rates being much smaller for warm ice-rich permafrost at temperatures close to 0 °C than for colder permafrost or bedrock.

These changes in the physical climate regime and cryosphere are already generating widespread ecological, human, and economic impacts, which are projected to intensify in the future. Changes in the cryosphere will cause fundamental changes to the characteristics of Arctic ecosystems and in some cases loss of entire habitats with consequences for people who receive benefits from these resources (SWIPA 2011). In the terrestrial ecosystems the dominant response of Arctic species to climate change will probably be relocation rather than on-site adaptation (IPCC WG2 2007). It is expected over time that forest will replace significant proportions of the tundra and that this again will have great effects on biodiversity which is projected to increase. According to SWIPA (2011), decreased multi-year sea ice and increased open water will enhance the overall marine production. Many marine ecosystems will be experiencing shifts from light limitation to nutrient limitations as well as shifting balance between the primary production by ice algae and phytoplankton with implications for Arctic food webs. Changing ice patterns and timing will affect mammals, including the polar bears, marine birds and some fish species. Pinniped species that depend on ice (i.e. seals and walrus) will be disadvantaged due to reductions in the sea ice extent. According to model projections, within 50-70 years loss of hunting habitats may lead to extirpation of the polar bears from seasonally ice-covered areas, where currently two thirds of their world population live. Sub-arctic seabirds will be competing with arctic species. Northward expansion of habitats for some temperate species will enhance foraging opportunities for their predators in the High Arctic, at a cost to endemic populations of the Arctic.

There are challenges for human systems, local communities and traditional ways of life. Infrastructure and settlements, particularly on the Arctic coasts, become more vulnerable with increased risks of damage due to the coastal erosion, permafrost degradation, and loss of sea ice (IPCC WG2 2007; SOAC 2011; SWIPA 2011). Human settlements and cities in the Russian Arctic are conventionally located along the rivers, and particular concerns are associated with floods caused by ice jams. This is exemplified by the catastrophic 2001 Lena River flood, which demolished most of the buildings in the city of Lensk. According to SWIPA (2011), floods due to ice jams on Siberian rivers in the coming decade are projected to become 1.2 to 1.5 times more frequent and more severe with 35 to 60% increase in peak break-up water levels. In north-European Russian rivers (Severnaya Dvina, Sukhon, Vyga, Pechora) maximum jam levels might increase by 10-12%, while the frequency of floods would increase by a factor of 1.2, at most. Such changes may have serious implications for settlements and infrastructure on the shores of these rivers, and many of the populated areas are expected to be periodically flooded. Transport options and access to resources are radically changed by differences in the distribution and seasonal occurrence of snow, water, ice and permafrost. Freshwater ice durations over much the circum-polar North have decreased since 1970s in response to earlier break-ups and later freeze-ups, on average 6.3 and 5.8 days/100 years, respectively, with rates in the high Arctic more than 4 times greater than those experienced in more southerly latitudes (SWIPA, 2011). Maximum ice thickness decreased up to 15 cm in rivers within Siberia. Statistically, a long-term mean increase of 2 to 3°C in autumn and spring air temperature produces an approximate 10 to 15 day delay in freeze-up and advance in break-up, respectively. As a result, many of the ice roads may become less viable option than the all-weather roads with implications for significantly increased costs (SWIPA, 2011). There will also be new opportunities such as increasingly navigable Northern Sea Route with up to 125 days per year suitable for navigation by 2050, and predicted up to 15% decline in the heating energy demand in the populated Arctic areas (IPCC WG2 2007). Reduced ice period and thickness of river ice is beneficial for hydropower generation during the low flow winter season, when the energy demand is at its annual maximum (SWIPA, 2011).

Arctic societies have a well-deserved reputation for resilience in the face of change. But today they are facing an unprecedented combination of rapid and stressful changes involving environmental processes, cultural developments, economic changes, industrial developments, and political changes. That may limit this resilience. As argued in the AR4, the most effective adaptation options will be those that recognize the nexus between adaptation and sustainable development (Yohe et.al., 2007 (IPCC WG2). One consequence of this observation is the potential of “mainstreaming” adaptation into existing policy processes and priorities (such as those for poverty alleviation, health standards, emergency planning and insurance) leading to “win-win” options.

Although climate change and other processes affecting the availability of natural resources impose large impacts on quality of life and economic activity for communities on the Arctic coast, other factors and processes will often be more important, especially in the short run. Where communities are already stressed, even small changes in the availability or quality of natural resources may be critical (SOAC 2011).

The holistic perspective of indigenous culture suggests that efforts to understand, manage, and respond to change in Arctic local communities and coastal systems may benefit from the integration of this knowledge with Western science. Recognizing the value of traditional ecological knowledge may contribute to enhanced resilience and adaptive capacity in local and coastal communities (E.g. SOAC 2011; SWIPA 2011).

Antarctic

While temperatures over the bulk of the Antarctic continent have not changed markedly in recent decades, the strongest rates of atmospheric warming seen in the Southern Hemisphere are occurring in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration (Mayewski *et al*., 2009; Turner *et al*., 2009; Stammerjohn *et al*., 2012). Although not to the same extent, warming has also occurred in the continental margins near to Bellingshausen Sea, Prydz Bay and the Ross Sea, with areas of cooling in between (Bromwich *et al*., 2013). Land regions that have experienced significant warming have seen considerable glacial recession along with changes in the ice and permafrost habitats in the coastal margins, although changes in snow fall show no trends. The Southern Ocean continues to warm throughout its depth with increased freshening at the surface due to precipitation, leading to increased stratification. The Antarctic Circumpolar Current has moved to the south, the extent of which is regionally variable. Similarly, the magnitude and southward extent of increasing wind-driven mixing associated with increasing SAM is also regionally variable (Sallee *et al*., 2010). Aragonite undersaturation of the Southern Ocean at depths equivalent to the continental shelf will occur within decades, with some regions being affected sooner than others. Undersaturation of the surface waters is likely before 2100, reinforcing previous conclusions of threats to pteropods (pelagic marine molluscs).

Antarctic terrestrial systems have been documented to have changed with increasing habitat from reduction in snow and ice cover resulting in increased abundance of flowering plants. On subantarctic islands there have also been increases in abundance of alien species and consequent negative impacts on local biota.
Antarctic terrestrial ecosystems occur in three generally accepted biogeographic regions; the sub-Antarctic, maritime Antarctic and Continental Antarctica, with generally warmer temperatures, reduced extreme seasonality and greater biodiversity in the sub-Antarctic (Convey, 2006). On the continent, where biological diversity is limited to species that can take advantage of the short periods where temperatures and moisture availability are above physiological and biochemical thresholds, recent research has shown that there are 15 biologically distinct areas (Terauds *et al*., 2012). In many areas there is no visible vegetation with life often limited to endolithic (within rock) communities of algae, cyanobacteria, fungi, bacteria and lichens (Convey, 2006).

Antarctic freshwater systems are fewer and much smaller than Arctic freshwater systems, comprising lakes, ponds, short streams and seasonally wetted areas (Vincent *et al*., 2008). Antarctic freshwater biota are dominated by benthic microbial communities of cyanobacteria and green algae in a simple food web. Mosses occur in some lakes but higher plants are absent on the continent. Planktonic ecosystems are dominated by small algae, bacteria and colourless flagellates. There are few metazoans and no fish. Documented effects of climate change include changing microbial dynamics in lakes as a result of changing nutrients and contaminants. For subantarctic islands, such as Signy Island, increased icefree conditions and temperatures along with decreases in perennial snow cover have led to increased organic and inorganic nutrient inputs to lakes. Fur seal populations have increased dramatically and occupied the increasing available terrestrial areas, resulting in disruption of local systems, including increased nutrients into the areas.

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry and light due to vertical mixing (Massom and Stammerjohn, 2010; Boyd *et al*., 2012; Constable *et al*., submitted). Diatoms are the dominant primary producers, particularly in the coastal waters, which are also the primary contributors to the annual carbon flux in the region. Antarctic marine food webs are dominated by Antarctic krill, *Euphausia superba* (hereafter termed 'krill'), which primarily consumes large phytoplankton (diatoms) and small zooplankton and are themselves food for many of the fish, squid, marine mammals, penguins and flying birds in the Southern Ocean. Other

secondary producers are salps and copepods, which can feed on smaller phytoplankton, and are consumed by smaller fish, such as myctophids. The relative importance of krill varies regionally, being dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean (Rogers *et al*., 2012). In the Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the Antarctic Circumpolar Current, while in the north the system is dominated by copepods and myctophid fish.

Around the Antarctic continent, the coastal systems are characterised by deep shelf areas (800m) broken by canyons and cross-shelf depressions (Grant *et al*., 2006). Banks of 300m depth or less are scoured by icebergs. Benthic communities are differentiated by these topographic features (Constable *et al*., submitted). Coastal polynyas are prevalent, caused by land forms, glacier tongues, bottom topography or grounded icebergs(Massom and Stammerjohn, 2010). These areas are high in productivity with a few areas being important for the formation of Antarctic Bottom Water, which sinks from the surface flowing over the shelf and into deep water, influencing the benthos with its water chemistry and organic particulates.

For these marine ecosystems, few studies were available in AR4 to document and validate the changes resulting from climate change. Those studies reported increasing sponges and their predators, declining abundances of krill, Adélie and Emperor penguins, and Weddell seals and a possible increase in salps in place of krill, noting regional differences in these trends. These changes may have been attributable to declining sea ice or as indirect consequences of recovery of whales and seals from past over-exploitation. The importance of climate change was not able to be determined. Future impacts of climate change included that increases in temperature and reduced sea ice were expected to negatively affect krill abundance and cause a shift in its distribution. As well, many cold-adapted species, though not all, may be vulnerable if water temperatures rise to 5-10oC. Overall, the direct and indirect effects of climate change were considered to be difficult to predict, particularly in relation to an increasing fishery for Antarctic krill.

Economic activities in the Antarctic have been limited to fishing and tourism (IPCC WG2 2007).

28.2. Observed Changes and Vulnerability under Multiple Stressors

28.2.1. Hydrology and Freshwater Ecosystems

28.2.1.1. Arctic

Rivers and lakes within the Arctic high latitudes continue to show pronounced changes to their hydrology, which can have cascading effects on their aquatic ecology. One of the most conspicuous hydrologic changes has been to river flow. Previously noted increases in Eurasian river flow (1936-1999)(Peterson *et al*., 2002) could not, for a similar period (1951-2000), be attributable with certainty to precipitation changes (Milliman *et al*., 2008), although decreases observed in the flow of major high-latitude Canadian rivers (1964-2000; average -10%) does match that for precipitation (Déry and Wood, 2005).

More recent discharge data (1977-2007) for 19 circumpolar rivers indicates an area-weighted average increase of +9.8% (range –7.1 to +47.0%; 15 of 19 exhibiting increases), with additional evidence of accelerating change in recent years for the combined domain of six selected large basins (Overeem and Syvitski, 2010). This has been accompanied by shifts in flow timing with the main month of snowmelt (May) increasing by an average 66% but flow in the subsequent month of peak discharge decreasing by ~7%. Across the Russian Arctic drainage basin, dates of spring maximum daily discharge have also become earlier, particularly in most recent [1960-2001] period analyzed (average -5d; range for four regions +0.2 to -7.1 d), although no consistent trend exists for changes in the magnitude (average -1%; range +21 to -24%) of these daily flows (Shiklomanov *et al*., 2007). Changes to earlier timing were most pronounced in eastern, colder continental climates that have experienced rises in air temperature. Such upward trends in air temperature, rather than flow regulation, have been identified as the dominant control of such timing shifts (Tan *et al*., 2011).

Changes have also occurred in winter flows with documented rises in the winter minimum flows for many Eurasian and North American rivers (Walvoord and Striegl, 2007; Smith *et al.*, 2007; St. Jacques and Sauchyn, 2009; Ye *et al.*, 2009) , the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm *et al.*, 2010). Most such studies suggest that winter flows have increased because of enhanced subsurface flow resulting from permafrost thaw (see WGI, Chapter 4), the concept supported in part by some satellite-gravity measurements (Muskett and Romanovsky, 2009). Others argue that the primary control is an increase in net winter precipitation minus evapotranspiration (Rawlins *et al.*, 2009a; Rawlins *et al.*, 2009b; Landerer *et al.*, 2010). Insufficient spatial coverage of Arctic precipitation stations precludes deciphering the relative importance of these two controlling factors.

Information about the changes to the hydrology and water budget of lakes is scarcer than that for rivers. Information from satellite thermal imagery, however, indicates that surface-water temperatures of large water bodies have been warming for the period 1985-2009 (Schneider and Hook, 2010). Greatest warming was observed for mid- and high latitudes of the northern hemisphere with the spatial patterns generally matching those for surface air temperature. Where water bodies warmed more rapidly than air temperature, decreasing ice cover was suggested as enhancing radiative warming.

Changes to terrestrial hydrologic and freshwater ice regimes have also produced a number of physical, geochemical and ecological effects on some arctic lake, wetland and river systems. Reduced ice cover accompanied by higher air temperatures and evaporation, have been identified as being responsible for the recent summer drying out of some Canadian High Arctic ponds, which had been permanent water bodies for millennia (Smol and Douglas, 2007a). Where water has persisted and lake-water temperatures increased, reductions in organic carbon burial has been attributed to a strong positive relationship with the mineralization of organic carbon in lake sediments (Gudasz *et al.*, 2010). Increasing water temperatures can also affect planktonic and benthic biomass in Arctic lakes and lead to changes in species composition (Heino *et al.*, 2009; Jansson *et al.*, 2010). In a study of a Greenland catchment, warmer conditions have been noted to increase nutrient and humic acid loadings leading to a higher abundance of phytoplankton and zooplankton (crustaceans) and altered species composition (Christoffersen *et al.*, 2008).

In the case of permafrost thermokarst lakes, new studies have documented changes in their size and number in various parts of the Arctic (Riordan *et al.*, 2006; Hinkel *et al.*, 2007; Marsh *et al.*, 2009). Their spatial patterns and rates of change, however, are not consistent and may be related to differing thawing state of the permafrost as well as spatial variations in warming (Prowse and Brown, 2010a). Thawing permafrost has also been identified as causing major changes to the biogeochemistry of water entering high-latitude lakes and rivers (Frey and McClelland, 2009), and to have implications for their ecological structure and function (Lantz and Kokelj, 2008; Mesquita *et al.*, 2010) , with some documented cases resulting in enhanced lake eutrophication through an ecological shift from pelagic-dominated to benthic-dominated production (Thompson, M., Wrona, F., Prowse,T., 2012).

The ecology of rivers has also been demonstrated to be dependent on changes to their freshwater ice regimes. Reductions in the physical severity of spring break-up (see WGI, Chapter 4) in the vast riparian zones of the Mackenzie River Delta has been observed to decrease the supply of ice-jam floodwaters and related nutrients and sediments to the delta's riparian zone, and hence, its ecological health (Lesack and Marsh, 2007). Such reductions in spring flood levels, combined with rising arctic sea level and sea ice recession, have also been proposed as the proximal drivers of biodiversity loss in this system. This is primarily related to the decline of lakes with short and variable hydrologic connection times, plus low and variable river water renewal (Lesack and Marsh, 2007). Because circumpolar river deltas act as biogeochemical processors of river water before its discharge to the Arctic Ocean (Emmerton *et al.*, 2008), changes in delta flooding could also affect primary production and food web processes in the coastal marine ecosystem, although these remain to be assessed. Changes to some near-coastal freshwater environments have been documented for the case of epishelf lakes (Veillette *et al.*, 2008). Such ice dependent freshwater lakes have become increasingly inundated with seawater as a result of the loss of integrity in their retaining ice dams (Vincent *et al.*, 2009), and as a result, the microbiologically rich ice shelve lakes are disappearing (Mueller *et al.*, 2008).

28.2.1.2. Antarctic

Recent compilations of single-year datasets have reinforced previous conclusions on the changing freshwater habitats in Antarctica (Verleyen *et al*., 2012). In regions where the climate has warmed the physical impacts on aquatic ecosystems include loss of ice cover, increasing periods of open water, increased water column temperatures and changes in water column stratification. Shifts in the water balance can also occur. In some areas a negative water balance has been established due to increased temperate and changes in wind strength driving enhanced evaporation and sublimation and leading to increased salinity in lakes (Hodgson *et al*., 2006a). In other areas, especially glacial forelands, increased temperatures lead to greater volumes of seasonal meltwater in streams and lakes together with increased nutrient fluxes. In both cases the balance between precipitation and evaporation can have detectable effects on lake ecosystems through changes in water body volume and lake chemistry (Lyons *et al*., 2006; Quesada *et al*., 2006). Non-dilute lakes with a low lake depth to surface area ratio are most susceptible to inter-annual and inter-decadal variability in the water balance, as measured by changes in specific conductance (Verleyen *et al*., 2012). In most cases warming is predicted to increase biological production in lakes. Other effects include dessication of moss banks due to increased evaporation and sublimation rates (Wasley *et al*., 2006), increases in the latitudinal ranges of extant species and increase the likelihood of invasive species becoming established together with increases in community biomass and complexity (Peck, 2005).

In summary, there is *high confidence* that increased temperatures will impact subaerial aquatic ecosystems in Antarctica. The exact nature of these impacts are likely to vary regionally depending on the magnitude of the temperature change, how much change in an area required for the temperature to rise above freezing, the depth to surface area of the lakes and the local hydrology. A great difficulty in documenting change is the absence of long term monitoring in most of Antarctica.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

Climate change is expected to affect physical and chemical properties of Arctic marine ecosystems by: (1) increasing temperatures, (2) altering the timing and extent of sea ice retreat, (3) changing sea water density through increased freshwater supply, (4) reducing sea ice thickness and multi-year ice formation which in turn changes the timing and duration of irradiance in the water column, and (5) ocean acidification (WG 1 Chapters 4 and 11). This section addresses the expected impacts of these physical and chemical changes on marine ecosystems.

Retrospective studies show the Arctic and its neighboring seas are influenced by interannual, decadal, and multi-decadal climate variations (WG 1). These variations in climate forcing are expected to continue in the future (Overland and Wang, 2010) and will continue to influence the ocean conditions in the Arctic (Ogi *et al*. 2010). For example, recent (2007-2012) ocean conditions in the Bering Sea have been cold (Stabeno et al. 2012), while the Barents Sea has been warm (Lind and Ingvaldsen, 2012).

Observations and model predictions indicate that the carbon cycle of the Arctic Ocean will be impacted by climate change. The processes that influence the inorganic carbon cycle in the Arctic are complex and differ seasonally and regionally (Bates and Mathis, 2009). The mechanisms underlying ocean acidification and the expected rates of change in ocean pH caused by increased CO_2 are documented in WG I Chapter 6 and II Chapters 5, 6, 19 and 30. If some regions in the Arctic become understaturated with respect to aragonite (the primary structural component of the shells of some marine calcifiers such as pteropods (small planktonic shelled mollusks), urchins, and clams the growth and survial of these organismswill be impacted (WG I, Chapter 6 Figure 6.28; Chierici and Fransson, 2009; Fabry *et al*., 2009; Yamamoto-Kawai *et al*., 2009). Additional monitoring and process studies are needed to fully understand how these processes will unfold in the future.

28.2.2.1.1. Overview of Arctic marine plankton and fish

Two sources of primary production include spring and fall ice algal blooms and pelagic blooms in response to the solar cycle and stratification (Wassmann, 2011). Large phytoplankton blooms can develop underneath the ice with implications for energy partitioning between pelagic and benthic ecosystems (Perrette *et al*., 2011; Arrigo *et al*., 2012). With the onset of the Arctic summer, sea ice begins to melt and the water column stratifies. The upper mixed layer of the Arctic Ocean is nutrient-rich and the combination of increased light and nutrients triggers spring bloom (Hirche *et al*., 2006; Zhang *et al*., 2010).

Copepods (small pelagic crustaceans) dominate the mesozoplankton community in the Arctic, where they are preyed upon by larger invertebrate predators, fish, seabirds and marine mammals. Four species of the genus *Calanus* are common, but only two, *C. glacialis* and *C. hyperboreus*, are true Arctic species (Ji *et al*., 2012). The other two, *C. finmarchicus* and *C. marshallae*, are boreal ex-patriot species that are brought north in the Atlantic and Pacific water inflows, respectively. All four Calanus species feed on phytoplankton, accumulating lipid (wax-esters) during the growth season, and spending some part of the year dormant (in diapause) below the surface layers. All four have reproductive cycles that take advantage of the spring bloom in some way and while the boreal species have annual life cycles, the Arctic species take two or more years to mature and reproduce. Other important large-bodied copepods are *Neocalanus cristatus* and *N. flemingeri* in the Bering Sea, which have life histories and feeding preferences similar to those of the *Calanus* species, and *Metridia longa*, which is abundant throughout the deep waters of the eastern and central Arctic (Kosobokova and Hirche, 2009), and which is active all year round, feeding omnivorously. In the Bering and Barents Seas, a large fraction of the phytoplankton biomass is retained in the pelagic system by zooplankton grazing (Riser *et al*., 2008), while farther north in the Chukchi Sea low grazing pressure results in underutilization of early spring production which in turn leads to export of carbon on the seafloor where it feeds a productive benthic ecosystem (Grebmeier *et al*., 2006; Riser *et al*., 2008).

Euphausiids (krill) are not endemic to the Arctic, but are brought into the region in the Atlantic and Pacific inflows. In the Barents Sea, krill (mainly *Thysanoessa inermis* and *T. raschii*) provide an important food source for several species of fish, including cod, haddock and capelin (Ressler *et al*. 2012; Dalpadado *et al*., 2008; Orlova *et al*., 2009; Dalpadado *et al*. 2009). In the west, euphausiids are transported north through the Bering Strait towards the Beaufort Sea, where aggregations are consumed by bowhead whales off Point Barrow, Alaska (Berline *et al*., 2008).

The broad shelf regions of the Barents and Bering Seas support abundant and diverse fish and shellfish populations. Farther north, fewer fish species are adapted to the short growing season, the delay in the emergence of copepods and the cold ocean conditions. In general, dominant pelagic species are smaller sized fish capable of rapid growth in the first year of life (e.g. capelin, *Mallotus villosus*) and in some cases antifreeze proteins to tolerate cold temperatures (e.g. polar cod, *Boreogadus saida*). Examination of the biogeography of species shows that potentially interacting species partition their habitat vertically and horizontally in response to competition, predation and environmental disturbance (Spebcer, 2008; Mueter and Litzow, 2008). Habitats are bounded by topographic features, fronts, currents or river plumes, and oceanographic features left by sea ice (including salinity fronts) (Ciannelli and Bailey, 2005). Over time fish and invertebrates have evolved life histories to reduce exposure to predation, maximize the probability of temporal and spatial overlap with prey concentrations, and support successful mating (Sundby and Nakken, 2008; Hunt *et al*., 2011; Mundy, 2011; Bouchard and Fortier, 2011; Hollowed *et al*., 2012).

Phenological responses (timing of spawning, timing of settlement, duration of growing season, age at maturity)

Changes in ocean temperature, wind-driven upwelling of deep nutrient-rich waters, sea ice thickness, the date of ice breakup and stratification will alter the timing, duration and magnitude of phytoplankton production (Zhang *et al*., 2010). During the period 1997-2009 a trend towards earlier phytoplankton blooms was detected in approximately 11% of the area of the Arctic Ocean (Kahru *et al*., 2011). This advanced timing of annual phytoplankton blooms coincided with the decreased sea ice concentration in early summer (Kahru *et al*. 2011). Given the short time series and limited studies, there is *medium confidence* that climate change will alter the bloom timing and the duration of phytoplankton trophic production in the Arctic.

There is *medium confidence* based on theoretical relationships and observations that rapid changes in physical and chemical changes in ocean conditions will alter the timing and duration of phytoplankton production. If shifts in timing disrupt the match between copepod hatch dates and spring production this would impact the survival of zooplankton and timing of spring prey availability for their predators (Søreide *et al*., 2010). However, simulation modeling of the Arctic Ocean and its surrounding Seas, showed longer growth seasons and increased summer temperature in the central Arctic favored endemic copepods (*Calanus glacialis* and *Calanus hyperboreus*) (Ji *et al*., 2012). Results from the cruises conducted during the International Polar Year in 2007 and 2008 on the Canadian shelf and adjacent open ocean and the southeast Beaufort Sea, suggest that longer ice free periods in the Arctic could provide for more opportunities for episodic nutrient pulses that would enhance secondary production through the growing season (Tremblay *et al*., 2012). Additional research is needed to understand how climate change will impact seasonal survival of Arctic zooplankton.

There is *medium* to *high confidence* based on observations of fish responses at lower latitudes, that climate change impacts on the physical and chemical environment in the Arctic will cause changes in phenology of some fish and shellfish species in the Arctic marine ecosystems. Several studies document that climate shifts and associated changes in ocean conditions impact the growth, spawning and feeding distribution and of marine fish (Gjosaeter et al 2009; Drinkwater eta l. 2011). The responses of fish to shifts in the timing and duration of growing seasons will vary by species. Some species exhibit an ability to adjust the timing of spawning and rates of growth to local conditions (Ormseth and Norcross, 2009; Kristiansen *et al*., 2011) however, these adjustments occurred over long time periods. However, compared to temperate regions, there is a general lack of long-term phenological studies from the Arctic Ocean and additional observations are needed.

Observed spatial shifts in response to climate

Considerable geographic variation in primary production has been observed (Lee *et al*., 2010; Grebmeier, 2012). Simulation studies revealed that longer growing seasons resulting from climate change will be insufficient to allow expatriate species to become endemic species in the Arctic Ocean (Ji *et al*., 2012). In the Barents Sea, simulation modeling experiments showed that summer loss of sea ice and increased temperature would impact the decrease the production of *C. glacialis* and increase the production of *C. finmarchicus* (Slagstad *et al*. 2011). In the Arctic Ocean, the observational record is often short or of limited spatial scale (Slagstad *et al*., 2011). Additional observations are needed to accurately predict shifts in the range of Arctic and sub-Arctic copepods in response to climate change.

Climate-related changes in the flow of currents into the Arctic will likely change the abundance and distribution of euphausiids. In the Barents Sea, in years when greater intrusions of Atlantic water occurred, higher temperatures and higher levels of euphausiids were observed, with varying species composition (Zhukova *et al*., 2009).

Numerous studies from the Bering Sea, Barents Sea, west Greenland Sea, and Chukchi Sea confirm that fish shift their spatial distribution in response to climate variability (i.e. interannual, decadal or multi-decadal changes in ocean temperature; (Mueter and Litzow, 2008; Sundby and Nakken, 2008; Hátún *et al*., 2009; Valdimarsson *et al*., 2012). Retrospective analysis of the spatial distribution of demersal fish species in the North Atlantic shows redistribution of some species along latitudinal and depth gradients that are consistent with bio-climate envelope models (Simpson *et al*., 2011). However, responses to climate change may follow nonlinear responses in the future because multiple factors influence the spatial distribution and abundance of marine fish throughout its life cycle including: suitable habitat availability, fidelity to spawning locations, diet diversity, physiological responses, spatial temporal overlap with prey, prey density, and competition (Planque *et al*., 2010; Kristiansen *et al*., 2011; Sigler *et al*., 2011). Coupled bio-physical models have been developed to assess the implications of climate change on the spatial distribution and abundance of multiple life stages of several marine species in the Bering and Barents Seas (Huse, 2008; Parada *et al*., 2010). These models have been successful in reproducing the observed spatial dynamics of the target species and in some cases studies are underway to evaluate their predictive skill. Qualitative vulnerability assessments indicate that the persistence of cold winter conditions in the Arctic coupled with the life history factors noted above will restrict or retard the movement of several sub-arctic fish and shellfish species into the Arctic (Hunt Jr. *et al*., 2013; Hollowed *et al*., In Press). In summary, there is *medium* to *high confidence* based

on observations and modeling of fish responses in the Barents and Bering Seas to climate shifts, that climate change impacts on the spatial distribution and volume of suitable habitat will cause shifts in the spatial distribution of some fish and shellfish species in the Arctic marine ecosystems. The spatial extent of these shifts and the time frame for change will depend on the vulnerability of different species to climate change and the strength of the species response. Compared to temperate regions, there is a general lack of long-term comprehensive monitoring of the spatial distribution of fish and shellfish stocks in the high Arctic Ocean.

Observed variations in fish and shellfish production in response to climate

Satellite derived estimates of primary production provide evidence of a 20% increase in primary production in the Arctic Ocean between 1998 and 2009 in response to extended ice free periods (Arrigo *et al.*, 2011). Other studies showed gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad *et al.*, 2011). Studies based on a short, 5 year (2004-2008), time series in the Canadian Basin found that after the spring bloom, increased warming, increased stratification, and decreased nutrients during the Arctic summer may favor smaller phytoplankton over large phytoplankton (Li *et al.*, 2009; Morán *et al.*, 2010). Additional observations over a broader spatial scale are needed to confirm this relationship. Additional observations will also help to resolve observed differences between in-situ and satellite derived estimates of primary production (Matrai *et al.*, 2013). In summary, climate change is expected to extend the duration of the growing season and upwelling is expected to bring nutrients to the surface which would favor phytoplankton production, however, these factors may be offset later in the year by increased stratification and nutrient depletion in summer. Based on this information, there is *medium confidence* that primary production will increase in the Arctic in response to climate change impacts on the duration of ice free periods in the Arctic Ocean.

In the Bering Sea, Observations over the most recent decade in the southeast Bering Sea showed *C. marshallae* were more abundant in cold years than warm years (Coyle *et al.*, 2011). Based on this study there is *low confidence* that climate change will reduce the abundance of C. *marshallae* in the Bering Sea. Additional observations are needed to confirm this response.

Numerous studies have identified statistical links between climate variability and the annual production of zooplankton and fish (Mueter *et al.*, 2007; Drinkwater *et al.*, 2010). The mechanisms underlying these statistical linkages are often well documented for commercially important species (Bakun, 2010). The vulnerability of different fish and shellfish species to the direct and indirect effects of climate change is governed by the exposure of the species to changing environmental conditions and fishing throughout its life history and across its geographic range (Beaugrand and Kirby, 2010) and the ability of the species to adapt or acclimate to changing conditions (Pörtner and Peck, 2010; Donelson *et al.*, 2011). In the eastern Bering Sea and Barents Seas, large interdisciplinary research programs have identified the mechanisms underlying these statistical relationships which provided the foundation for climate change projections for selected species (discussed in section 28.3.2; Brander, 2010; Wiese *et al.*, 2012). Observations of the condition of age-0 pollock in the Bering Sea during the last decade showed condition improved in cold years suggesting that overwintering success was higher in years when *C. marshallae* were abundant (Hunt *et al.*, 2011). Retrospective studies of ocean conditions and interannual variations in walleye pollock recruitment to the fishery over three decades revealed a dome-shaped functional relationship between temperature and recruitment (Mueter *et al.*, 2011).

Other stressors

If the expected changes in summer sea ice occur as described by WG 1, opportunities for increased oil and mineral extraction, shipping, fishing and tourism are expected to occur in the region. These activities will increase the risk of introductions of alien species to the region and the risk of regional pollution.

The implications of ocean acidification on the food web can be considerable. If regions of the Arctic become understaturated with respect to aragonite, and this inhibits shell formation for pteropods, this will have strong consequences on their predators. At the current time it is not possible to fully predict the consequences because it is

unclear whether other species, with a similar nutritive value, will replace pteropods. Laboratory experiments showed a decline in the calcification of a pteropod (*Limacina helicina*) in the Arctic under projected ocean warming and acidification (Comeau *et al.*, 2010). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on *Limacina helicina* and other vulnerable species (Orr *et al.*, 2009). The lack of systematic sampling over large areas of the Arctic and the paucity of experimental studies examining the response of marine organisms to multiple stressors impede the ability to project when and where waters will become understaturated in aragonite in the Arctic and the vulnerability of calcifying marine organisms to understaturated waters

28.2.2.1.2. Current changes in Arctic seabird populations

Upwelling or convergence areas found in frontal zones and eddies, and the marginal ice zone, are associated with high marine productivity important to Arctic seabirds (e.g. (Irons *et al.*, 2008). Long-term or permanent shifts in convergence areas and the marginal ice-edge zone induced by climate change may cause mismatch between the timing of breeding and the peak in food availability and, thus, potentially have strong negative impacts on seabird populations (Gremillet D. and Boulinier T., 2009).

Such spatial mismatch between prey base and breeding has been documented for a few seabird populations. The percentage of important prey in the diet of a declining black guillemot (*Cepphus grylle*) colony in the western Beaufort Sea was highly negatively correlated throughout the breeding season with changes in the distance to the ice edge which was the habitat of the prey (Moline *et al.*, 2008). Since 1990, breeding success and population size have been negatively correlated with summer pack-ice extent.

Even though timing of breeding advanced for Brünnichs guillemots (*Uria lomvia*) in a colony in the southernmost part of its range in Arctic Canada between 1988 and 2007, it did not advance sufficiently to match the advance in break up of sea ice which is associated with high prey availability. Less ice cover was correlated with lower chick growth rates and lower adult body mass, suggesting that reduction in summer ice extent had a negative effect on reproduction (Gaston *et al.*, 2005; Gaston *et al.*, 2009). Current trends suggest that continued warming should benefit birds breeding on the northern limit of the species range, while adversely affecting reproduction for those on the southern margin (Gaston *et al.*, 2009).

In contrast, (Byrd *et al.*, 2008) could not document any significant correlation between productivity of brünnichs guillemots and common guillemots (*Uria algae*) breeding on the Pribilof islands in the Bering Sea and changes in sea ice extent 1976-2006. Kittiwakes (*Rissa tridactyla and Rissa brevirostris*), however, breeding in colonies on the same islands, advanced their timing of breeding by half to almost one day per year and reduced their productivity in correlation with less sea ice and higher Sea Surface Temperatures (SSTs). In the North-Atlantic Svalbard islands, kittiwakes responded differently - by showing a non-significant trend for later egg-laying when SSTs increased and ice cover was reduced (Moe *et al.*, 2009).

The circumpolar populations of the two closely related common guillemot and Brünnichs guillemot declined when the SST shift was large and increased when the shift was small, although the effect differed between the Arctic-breeding species and the more temperate-breeding congener (Irons *et al.*, 2008). A major ecosystem shift in the Northern Bering Sea starting in the mid 1990tiescaused by increased temperatures and reduced sea ice cover had a negative impact on benthic prey for diving birds like eiders and these populations in the area have declined (Grebmeier *et al.*, 2006).

Karnovksy et al. (2010) projected changes in SST in the Greenland Sea at the end of the 21st century and concluded that 4 of 8 little auk (*Alle alle*) breeding colonies in the North Atlantic may be negatively impacted as temperatures exceed the thermal range suitable for their preferred prey, the large lipid-rich Arctic copepods *Calanus glacialis and C. hyperboreus*. Little auks in Svalbard also responded by advancing the date for egg-laying when SSTs increased and sea ice cover was reduced (Moe *et al.*, 2009).

The contrasting results from the relatively few studies of impacts of climate change on arctic seabirds, demonstrates that it is likely that future impacts will be highly variable between species and between populations of the same species. Retreating sea ice and increasing SSTs have favored some species and been a disadvantage to others. While phenological changes and changes in productivity of some breeding colonies related to climate changes have been observed, changes in population size or projected expansion of the northern range accompanied by a contraction of the southern range is not well documented (Gaston and Woo, 2008).

The coupled oceanographic models and ice models project a significant reduction in sea ice extent in this century and increasing SSTs in the Arctic (Wang and Overland, 2009). The high Arctic seabird species partly or completely dependent on the productivity of the sympagic ecosystem or the cold Arctic waters close to the ice-edge, like the ivory gull, Brünnichs guillemots and little auks, will with *high confidence* be negatively impacted if the projected changes in these physical parameters occur. A moderate retreat of the marginal ice-zone and earlier break-up of sea ice may improve foraging conditions for some of these sea bird populations in the northernmost part of their range (Gaston *et al*., 2005). The distance to suitable nesting localities could be too great (within 200 km) for the birds to utilize the marine productivity in the ice edge zone if a main part of the zone stays over the deep Arctic Ocean during the breeding season.

A general increase in SSTs and retreat of the ice cover will with *medium confidence* improve the environmental conditions and food abundance for sea bird species that have their range in the southern part of the Arctic or south of the Arctic. A poleward expansion of the range of these species is expected during a continued warming (ACIA 2005). Several other factors than climate influence on the dynamics of sea bird populations (Regular *et al*., 2010), however, and projections of future changes during a continued Arctic warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA 2005). At present, the resolution of AOGCMs is not detailed enough to project spatial changes in mesoscale oceanographic features like frontal zones and eddies of importance to sea birds in the Arctic.

28.2.2.1.3. Polar bears

Both empirical and modelling studies have been used to understand the impacts of climate change on polar bears (*Ursus maritimus*) (Hunter *et al*., 2010; Amstrup *et al*., 2010; Durner *et al*., 2011). Empirical studies provide the most direct insight into the mechanisms of change but modelling allows improved predictive capacity.

Polar bears evolved from brown bears (*U. arctos*) and despite episodic admixture, the polar bears genome shows Arctic adaptations (Miller *et al*., 2012). Sea ice is the primary habitat of polar bears and is used for migration, mating, some maternity denning, and access to prey. Annual ice over the continental shelves is preferred due to high prey density (Durner *et al*., 2009). There is *high confidence* that the primary conservation concern for polar bears, over the foreseeable future or three generations (ca. 36-45 years), is the recent and projected loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness (Stirling and Derocher, 1993; Derocher *et al*., 2004; Stirling and Parkinson, 2006; Durner *et al*., 2009; Amstrup *et al*., 2010; Hunter *et al*., 2010; Rode *et al*., 2012; Sahanatien and Derocher, 2012).

Subpopulation response varies geographically reflecting differences in ice change. Only 2 of the 19 subpopulations, Western Hudson Bay (Regehr *et al*., 2007) and the Southern Beaufort Sea (Regehr *et al*., 2010; Rode *et al*., 2010a) have data series adequate for clear identification of abundance effects related to climate change. Other subpopulations lack adequate time series, but show characteristics associated with decline. For example, between 1977 and 2010, declining body condition in Baffin Bay and Davis Strait was associated with ice loss although high bear density was an alternate cause in the case of Davis Strait (Rode *et al*., 2012). Similarly, late arrival of ice at one Barents Sea denning area was associated with lower body mass of both mothers and their cubs (Derocher *et al*., 2011). There is *high confidence* that the primary conservation concern for polar bears is ice change that result in habitat loss and fragmentation causing reduced food intake, increased energy expenditure, and increased fasting (Stirling and Derocher, 1993; Stirling, I. *et al*. 1999; Mauritzen *et al*., 2003; Derocher *et al*., 2004; Regehr *et al*., 2007; Amstrup *et al*., 2010; Sahanatien and Derocher, 2012). There is *high confidence* for declining ice causing lower body condition that can reduce individual growth rates (Rode *et al*., 2010a; Rode *et al*., 2012) and *very high*

confidence that reduced body condition is a precursor to demographic change. Reduced body condition may result in lower fasting endurance, lower reproductive rates, and lower survival (Regehr *et al*., 2007; Regehr *et al*., 2010; Molnar *et al*., 2011) and these changes can reduce subpopulation growth rate or cause subpopulation decline (Derocher and Stirling, 1996; Derocher and Stirling, 1998; Stirling et. al., 1999; Regehr *et al*., 2010; Hunter *et al*., 2010; Rode *et al*., 2010a; Robinson *et al*., 2011). The Southern Beaufort Sea is projected to decline by 99% by 2100 with a probability estimated at 0.80-0.94 under A1B (Hunter *et al*., 2010). The Northern Beaufort Sea is currently stable although decline is predicted with warming (Stirling *et al*., 2011). There is *medium confidence* for subpopulation decline by 21% between 1987 and 2004 in Western Hudson Bay related to climate change (Regehr *et al*., 2007). Projected extirpation of approximately two-thirds of the world's polar bears was predicted for mid-century due to ice loss under A1B (Amstrup *et al*., 2008). Aspects of this study were criticized (Armstrong *et al*., 2008) but refuted (Amstrup *et al*., 2009). The two-thirds decline is consistent with other studies and has *robust evidence* with *medium agreement*. Projected extinction of polar bears has *low confidence*. There is *very high confidence* that subpopulation extirpation will occur with the projected climate change for the Arctic

Multiyear ice is used by some polar bears at maximal ice melt (Ferguson *et al*., 2010). Replacement of multiyear ice by annual ice could increase polar bear habitat (Derocher *et al*., 2004) but there is *low confidence* in habitat improvement. Increasing the distance to terrestrial refugia and multiyear ice at maximal melt may have negative consequences such as drowning, cub mortality, and high energetic costs (Monnett and Gleason, 2006; Durner *et al*., 2011; Pagano *et al*., 2012). Loss of multiyear ice may pose difficulties for some subpopulations although there is *limited evidence*.

There is *high confidence* in *robust evidence* of changes in sea ice conditions changing polar bear distribution (Fischbach *et al*., 2007; Schliebe *et al*., 2008; Gleason and Rode, 2009; Towns *et al*., 2010). Later formation and arrival of autumn ice at a Svalbard denning area reduced access to pregnant females (Derocher *et al*., 2011). Increased human-bear interactions were associated with distribution shifts and declines in body condition (Towns *et al*., 2009). There is *high confidence* that the number of human-bear interactions will increase with warming (Stirling and Derocher, 1993; Derocher *et al*., 2004; Stirling and Parkinson, 2006; Towns *et al*., 2009).

An increasingly terrestrial niche for polar bears was postulated (Dyck *et al*., 2007; Dyck and Romberg, 2007; Armstrong *et al*., 2008; Dyck *et al*., 2008; Dyck and Kebreab, 2009; Rockwell and Gormezano, 2009; Smith *et al*., 2010). However, such terrestrial feeding is not new (Lønø, 1970; Lunn and Stirling, 1985; Derocher *et al*., 1993; Derocher *et al*., 1993; Derocher *et al*., 2000). Assertions of an increased terrestrial niche for polar bears have been challenged because resources are inadequate to replace the high-energy content of marine prey (Derocher *et al*., 2004; Stirling *et al*., 2008b; Amstrup *et al*., 2009; Slater *et al*., 2010; Rode *et al*., 2010b). *Very low confidence* exists that polar bears can adapt to an increase in terrestrial foods. There is *very high confidence* that polar bears will not adapt to climate change in many subpopulations. Studies have also tentatively linked changing environmental conditions to cannibalism (Amstrup *et al*., 2006), altered feeding (Cherry *et al*., 2009), unusual hunting behaviour (Stirling *et al*., 2008a), and diet change (Iverson *et al*., 2006; Thiemann *et al*., 2008). There is *medium confidence* that these observations of polar bear may be related to changing ice conditions.

28.2.2.1.4. Arctic and subarctic marine mammals

Empirical studies on responses of Arctic and subarctic marine mammals to climate change are limited (Kelly, 2001; Laidre *et al*., 2008) . Understanding of climate change effects on marine mammals varies according to insight into their habitat requirements and trophic relationships. Many Arctic and subarctic marine mammals are highly specialized, have long-life spans, and are poorly adapted to rapid and directional environmental change (Moore and Huntington, 2008). Predicted changes, however, may not be evident until significant sea ice loss has occurred (Freitas *et al*., 2008; Laidre *et al*., 2008). Two Arctic ice-dependent seals (ringed seals, *Pusa hispida*, and bearded seals, *Erignathus barbatus*) and four ice-associated subarctic species (spotted seal, *Phoca largha*, ribbon seal, *P. fasciata*, harp seal, *Pagophilus groenlandicus*, and hooded seal, *Cystophora cristata*) use ice but none year-round (Lydersen and Kovacs, 1999). Similarly, walrus (*Odobenus rosmarus*) rely on ice for part of their life cycle but commonly retreat to land when ice is unavailable. Three cetaceans remain in the Arctic year-round (bowhead whale,

Balaena mysticetus, narwhal, *Monodon monoceros*, and beluga, *Delphinapterus leucas*) with narwhal the most ice-associated.

There is *high confidence* that climate change effects on Arctic and subarctic marine mammals will vary. Depending on life history characteristics, distribution, and habitat specificity, climate change will improve conditions for a few species, have minor negative effects for others, and some will suffer major negative effects (Ragen *et al.*, 2008; Laidre *et al.*, 2008). Resilience to climate change will vary and some ice-obligate species should survive in regions with sufficient ice and some may adapt to ice-free conditions (Moore and Huntington, 2008). Moore and Huntington (2008) suggest that less ice-dependent species may be more adaptable and could benefit from a longer feeding period but an increase in seasonally migrant species could increase resource competition.

Arctic and subarctic marine mammal vulnerability to climate change was associated with feeding specialization, ice dependence, and ice reliance for prey access and predator avoidance (Laidre *et al.*, 2008). There is *medium agreement* on which species' life histories are most susceptible to climate change. Hooded seals and narwhal were identified as most at risk and ringed seals and bearded seals as least sensitive (Laidre *et al.*, 2008). Kovacs *et al.* (2010) shared concern for hooded seals and narwhal but had serious concerns for ringed seals and bearded seals. Physiological specialization by narwhal suggests they may have limited ability to respond to habitat alteration (Laidre and Heide-Jørgensen, 2005); Williams *et al.* 2011). Species that spend only part of the year in the Arctic, such as the gray whale (*Eschrichtius robustus*) and killer whale (*Orcinus orca*) may benefit from reduced ice cover due to increases in prey availability (Moore, 2008; Laidre *et al.*, 2008; Higdon and Ferguson, 2009; Matthews *et al.*, 2011; Ferguson *et al.*, 2012). Expansion of killer whales into the Arctic could cause a trophic cascade with the polar bear-seal predator-prey linkage replaced with killer whales as the top predator (Higdon and Ferguson, 2009) although there is *limited evidence* at this time.

There is *limited evidence* although *moderate agreement* that generalists and pelagic feeding species may benefit from increased marine productivity resulting from reduced ice while benthic feeding ice-dependent species near continental shelf habitats may do poorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary or habitat specialists such as walrus will do poorly with reduced ice Changes in ice dynamics can cause walrus calves to become separated from their mothers during rapid ice retreat and may effect recruitment (Cooper *et al.*, 2006). Reduction of summer/autumn ice was identified as the primary extrinsic factor affecting Pacific walrus with predictions of distribution changes and longer-term predictions of high extinction probability (Maccracken, 2012). Retreat of summer ice was suggested to make migration to such habitats energetically unprofitable for ringed seals (Freitas *et al.*, 2008). Further, loss of ice in the Baltic Sea was identified as the primary threat to the Baltic ringed seal (Kovacs and Lydersen, 2008). Earlier break-up in the eastern Beaufort Sea had negative impacts on ringed seal pup growth and condition, and possibly on pup survival (Harwood *et al.*, 2000). Similarly, in Hudson Bay, earlier spring break-up and changes in snow cover over lairs used for reproduction has reduced ringed seal recruitment in recent years (Ferguson *et al.*, 2005). Further, changes in snowfall over the 21st century were projected to reduce the area of ice with sufficient snow for ringed seal lairs by 70% (Hezel *et al.*, 2012). Similarly, harp seal breeding habitat was affected by reduced ice duration and shifts in reproductive habitats, and an increase in the frequency of poor ice years could reduce survival of young (Bajzak *et al.*, 2011). While there is *limited evidence*, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, shipping, and development) (Burek *et al.*, 2008).

There is *high confidence*that the effects on Arctic and subarctic marine mammals will vary spatially and temporally, with some populations affected earlier than others and thereby making trends and effects difficult to detect (Kelly, 2001; Laidre *et al.*, 2008). There is *high agreement* that many Arctic and subarctic ice-associated marine mammals will be affected by ice loss with altered species distributions, migration patterns, behaviour, interspecific interactions, demography, population declines, and vulnerability to extinction but there is *limited evidence* of changes for most species.

28.2.2.2. Antarctic

28.2.2.2.1. Vulnerability and change

Evidence is accumulating to conclude that the distributions of Southern Ocean pelagic species (phytoplankton and zooplankton) have moved south with the frontal systems (Hinz, Poulton et al. 2012; Mackey, Atkinson et al. 2012). This is also confirmed by observed range expansion into the Southern Ocean from the north by the coccolithophorid, Emiliania huxleyii (Cubillos, Wright et al. 2007), and the red-tide dinoflagellate Noctiluca scintillans (McLeod, Hallegraeff et al. 2012).

The observed occurrence of lithodid crabs on the continental shelf of the west Antarctic Peninsula (WAP) has been attributed to movement south of warmer waters (Smith, Grange et al. 2012). These crabs will potentially impact the structure and diversity of benthic assemblages because of their ability to crush echinoderms and other taxa along with their bioturbating behaviour. However, direct evidence of the invasion of these crabs or the magnitude of impacts that they may have in the region has yet to be observed. There is no evidence to date of climate change impacts on the distributions of cold-adapted fish, although this remains a valid expectation for many species (Constable et al., submitted).

Physiological responses will vary among polar organisms (Constable et al., submitted) but an important response of many biota will be to ocean acidification (Byrne 2011). Shell thickness in foraminifera in the Southern Ocean are thinner than in the Holocene and there is evidence of a relationship between shell thickness and atmospheric CO2, supporting the hypothesis that ocean acidification will affect this abundant protozoan in the Southern Ocean (Moy, Howard et al. 2009). Recent studies of arogonite-shelled pteropods indicate that they are vulnerable to the effects acidification (Comeau, Alliouane et al. 2012; Comeau, Gattuso et al. 2012) and that shells are thinner from sediment traps in aragonite under-saturated water (below the aragonite saturation horizon - ASH) compared to those captured above the ASH in Subantarctic waters (Roberts, D. et al. 2011). However, the absence of time-series of samples related to change in the depth of the ASH and aragonite saturation generally makes it difficult to conclude how shell composition will be affected by changes to oceanic aragonite saturation (Roberts, D. et al. 2011). There is evidence that shell dissolution has already been observed in surface waters in the Atlantic sector as a result of both upwelling and atmosperhic changes in CO2 (Bednarsek, Tarling et al. 2012). Other impacts of acidification on Southern Ocean organisms are currently uncertain, but short term negative impacts need to considered together with an organism's capacity to adapt in the longer term (Watson, Peck et al. 2012).

Collapse of ice shelves may alter the dynamics of benthic assemblages by opening up areas previously covered by ice shelves and allowing increased primary production as well as colonisation and establishment of new assemblages, such as occurred with the collapse of the Larson A/B ice shelves (Peck, Barnes et al. 2009; Gutt, Barratt et al. 2011). Increased production of icebergs may increase the number of grounded icebergs causing changes in local oceanography and declines in productivity that consequently affects productivity of benthic assemblages (Thrush and Cummings 2011), or they may result in increased scour on shallow banks, disrupting resident benthic assemblages (Barnes and Souster 2011; Gutt, Barratt et al. 2011).

28.2.2.2.2. Productivity and krill

Primary production is expected to be changing regionally in the Antarctic in response to changes in sea ice, glacial melt and oceanography (Arrigo, van Dijken et al. 2008; Boyd, Arrigo et al. 2012). To date, the most compelling results of the effects of change in the physical environment on primary production and microbial assemblages is from the west Antarctic Peninsula region where (Montes-Hugo et al., 2009) reported decreased phytoplankton stocks and productivity (based on time-series of satellite-derived and measured chlorophyll concentrations) north of 63°S i.e., around the Antarctic Peninsula, and increases in these properties to the south of 63°S (see WGII Chapter 6 for discussion). They also indicated a change from diatom-dominated assemblages to ones dominated by smaller phytoplankton.

Densities of Antarctic krill have been estimated to have declined by approximately 30% in the Scotia Sea since the 1980s (Atkinson, Siegel et al. 2004), in parallel with declines in the extent and season duration of winter sea ice in the region (see (Flores, Atkinson et al. 2012) for review). The degree to which the overall abundance of krill has declined is still a matter of conjecture because the results are based on densities measured using different nets and different times, with results often biased downwards, particularly in krill swarms (Nicol and Brierley 2010). However, the observed dependence of Antarctic krill on the annual extent of winter sea ice (Nicol, Worby et al. 2008) indicates strong grounds for concern that the krill population in this key area where 70% of the population is found (Atkinson, Siegel et al. 2009) may have already changed and will be subject to further change.

Analyses of krill population dynamics suggest that changes in recruitment of post-larval krill across the Scotia Sea are linked to variations in surface temperature and sea-ice extent. Recent simulation modelling of krill productivity and dynamics show the plausibility of the positive relationship between sea ice extent and recruitment of krill in the Antarctic Peninsula region (Wiedenmann, Cresswell et al. 2009). However, such a decline may be offset by increased productivity arising from increased water temperature in that area (Wiedenmann, Cresswell et al. 2008). That said, the latter study also showed that krill productivity may decline in the South Georgia area as a result of the increased metabolic costs of increasing temperatures. The combined effects of changing sea ice, temperature and food have not been investigated.

Recently, krill have been discovered to be sensitive to ocean acidification. Experiments have shown that krill larval development (Kawaguchi, Kurihara et al. 2011) and post-larval krill metabolic physiology (Saba, Schofield et al. 2012) may be impeded by elevated CO2 concentrations.

28.2.2.2.3. Food web effects

The switch from a krill-based food web to a copepod- and fish-based food web in times of low abundance of krill in around subantarctic islands in the southwest Atlantic suggests that the latter may become more dominant around these islands in the future (Trathan, Forcada et al. 2007; Shreeve, Collins et al. 2009; Waluda, Collins et al. 2010). Also, salps have been postulated to be competitors with krill for phytoplankton around the Antarctic Peninsula when oceanic conditions displace shelf and near-shelf waters during times of low sea ice (Ducklow, Clarke et al. 2012). The trophic efficiency of these longer food webs in the absence of krill is less (Murphy, J. et al. 2013) and the long-term implications of this for higher trophic levels are unknown.

The changes in the physical habitat to the west of the Antarctic Peninsula (WAP), including the movement south of the sea ice extent, are believed to be resulting in a shift of the krill-dominated food web (krill, Adélie penguins and ice-breeding seals) to higher latitudes (Forcada, Trathan et al. 2012) and the replacement of this food web at lower latitudes with one composed of species that that do not depend on sea ice and are more able to exploit a range of prey items, for example gentoo penguins and elephant seals (Costa, Huckstadt et al. 2010; Trivelpiece, Hinke et al. 2011; Ducklow, Clarke et al. 2012; Murphy, Watkins et al. 2012b). The mechanisms driving these changes are currently under review and may be more complex than a simple association with sea ice (Lynch, Naveen et al. 2012; Melbourne-Thomas, Constable et al. 2013). This shift may be accompanied by an overall decline in the productivity of the WAP shelf (Montes-Hugo, Doney et al. 2009), although this may be tempered by increased inputs of iron through changes to ocean processes in the region (Dinniman et al., 2012).

28.2.2.2.4. Marine mammals and birds

The response of marine mammals, penguins and flying birds will be a complex response to a number of direct and indirect effects and may result either increasing or decreasing abundance depending on the regional effects of climate change on their habitats and food. In general, many Southern Ocean seals, penguins and flying birds are exhibiting strong responses to a variety of climate indices, with many, but not all, species showing a negative response to warmer conditions (Barbraud *et al.*, 2012; Forcada *et al.*, 2012). Adelie and chinstrap penguins have been declining in the north of the Antarctic Peninsula (Lynch *et al.*, 2012) while gentoo penguins are increasing in that region. In contrast, Adelie penguins may be increasing in east Antarctica (Constable *et al.*, submitted). There is

increasing evidence that emperor penguins may be declining throughout the Antarctic (Barbraud *et al.*, 2008; Jenouvrier *et al.*, 2009; Trathan *et al.*, 2011). Declines in seal and seabird populations in the subantarctic of the Indian sector of the Southern Ocean have been interpreted as a region-wide shift to a system with lower productivity (Weimerskirch *et al.*, 2003; Jenouvrier *et al.*, 2005a; Jenouvrier *et al.*, 2005b).

Direct effects on penguins include changes in location and conditions of foraging habitats as a result of shifting ocean conditions and sea ice extent near to breeding colonies, as well as increased precipitation in the colonies. Some of these responses may be dependent on local populations or colonies (Lynch *et al.*, 2012; Barbraud *et al.*, 2012) or may be regional differences. For example, Adelie and emperor penguins are postulated to have dome-shaped relationships between their demographic success and sea ice extent (see (Barbraud *et al.*, 2012) for review) rather than a simple monotonic relationship but the nature of such a relationship remains to be determined. A contributing factor to the reduction in Adélie penguins may be increased snow precipitation which accumulates in the breeding colonies and, when accompanied by reduced food supply, can decreases survival of chicks (Chapman *et al.*, 2011).

Movement south of the frontal systems, and therefore movement of productive foraging areas, in the Indian sector have been attributed to causing declines in King penguin colonies on subantarctic islands in that sector(Peron *et al.*, 2010), while the shift in wind patterns may be causing changes to the demography of albatross(Weimerskirch *et al.*, 2012).

As identified in the last assessment, change in some species may be a result of incidental mortality in fisheries or recovery from past over-exploitation, both of which may confound interpretation of the response of these species and their food webs to climate change. The recovery of Antarctic fur seals has been well documented. More recently, there has been confirmation of some Antarctic whale populations recovering, such as humpback whales(Nicol *et al.*, 2008; Zerbini *et al.*, 2010), suggesting that food is currently not limiting. In contrast, albatross and petrel colonies are declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall *et al.*, 2012).

28.2.3. Terrestrial Ecosystems

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 130 000 years) mainly driven by natural climate change. Significant altitudinal and latitudinal advances and retreats in tree line have been common, animal species have gone extinct, and animal populations have fluctuated significantly throughout this period e.g. (Lorenzen *et al.*, 2011; Salonen *et al.*, 2011; Mamet and Kershaw, 2012).

28.2.3.1. Phenological Responses

Phenological responses attributable to warming are apparent in Arctic terrestrial ecosystems (*medium confidence*). Compared to temperate regions, there is a general lack of long-term phenological studies from the Arctic. Phenological responses to warming vary from little overall trend in the Swedish sub Arctic (Molau *et al.*, 2005), despite accelerated recent warming (Callaghan *et al.*, 2010), to dramatic earlier onset of plant reproductive phenophases of up to 48 days in west Greenland (Post *et al.*, 2009a; Callaghan *et al.*, 2011a). Other substantial changes include earlier clutch initiation dates in birds and earlier emergence of arthropods in northeast Greenland (Figure 28-2) (Høye *et al.*, 2007).

[INSERT FIGURE 28-2 HERE
Figure 28-2: Advancement of phenological events in high-Arctic Greenland. a) location of the study area Zackenberg, North-east Greenland. b) Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initation dates (birds). Red dots are statistically significant, blue dots are not (Høye et al., 2007).]

28.2.3.2. Observed Changes in Tundra Vegetation

The abundance and biomass of deciduous shrubs and graminoids (grasses and grass-like plants) have increased substantially over large – but not all – parts of the Arctic tundra in recent years (*very high confidence*). Most of this increase in deciduous shrubs can be attributed to Arctic warming (*very likely*), but in some parts of northwest Eurasia a portion of the graminoid increase seems tied to steadily intensifying reindeer grazing/trampling coupled with large-scale hydrocarbon extraction in recent decades(Forbes and Stammler, 2009; Kumpula *et al.*, 2011; Kumpula *et al.*, 2012) .

Recent assessments of changes in NDVI (Nomrlaized Difference vegetation Index, a proxy for plant productivity) from satellite observations between 1982 and 2010 show a substantial greening over large parts of the Pan-Arctic (Zhang *et al.*, 2008; Bhatt *et al.*, 2010; Walker *et al.*, 2011; Xu et al. 2013) (Figure 28-3) with the greatest increases in the North American high Arctic and along the Beaufort Sea, and in northern Canada (Pouliot et al. 2009). In contrast, decreases in NDVI were generally observed in South-western Alaska and easternmost Russia and occurred locally in the western Russian Arctic.
However, the east European Arctic (Nenets Autonomous Okrug) registers a significant increase in NDVI during this same time period (Macias-Fauria *et al.*,2012 ; Raynolds *et al.*, 2008; Bhatt *et al.*, 2010; Forbes *et al.*, 2010; Xu et al. 2013).

[INSERT FIGURE 28-3 HERE
Figure 28-3: Significant changes ($p < 0:05$) in aboveground tundra phytomass from 1982 to 2010 (Epstein et al. 2012).]

The positive trends (1982-2010) in NDVI are associated with increases in the summer warmth index (sum of the monthly-mean temperatures above freezing expressed as ºC per month) that have increased on average by 5ºC per month for the Arctic as a whole(Xu et al. 2013). However, the even greater 10 to 12ºC per month increase for the land adjacent to the Chukchi and Bering Seas (Figure 28-3) was associated with decreases in NDVI, indicating that other factors than increased warming also affect NDVI and plant growth. On the Yamal Peninsula in Russia the pattern of NDVI is partly due to surface disturbance, such as landslide activity particularly in the central and northern portions (Walker *et al.*, 2009). Small rodent cycles reduce NDVI in sub Arctic Sweden, by decreasing biomass and changing plant species composition (Olofsson *et al.*, 2012). This indicates that the changing NDVI signal should be interpreted with care in general. Increases in land surface temperatures and NDVI in some areas have been related to earlier retreat of coastal sea ice in early summer (Bhatt *et al.*, 2010), but the relationship between sea ice and NDVI is restricted to early spring in northwest Eurasia (Macias-Fauria et al. 2012).

Since IPCC AR4, increasing evidence from studies that range in scale from landscape to experimental plots, shows that one of the greatest vegetation changes is the areal expansion, in-filling (densification) and increased growth of woody plants (trees and shrubs) (Myers-Smith *et al.*, 2011a; Callaghan *et al.*, 2011b; Elmendorf *et al.*, 2012 aand b) Observations extend back 100 years but most evidence comes from changes that have occurred over approximately the past 20 years.. Shrubs have generally expanded their ranges (Myers-Smith *et al.*, 2011a; Callaghan *et al.*, 2011b; Elmendorf *et al.*, 2012b) and/or growth for example in Alaska (Tape et al. 2001; Sturm et al. 2006), the Yukon region of Canada (Myers-Smith *et al.*, 2011a), southeast Yukon (Danby and Hik, 2007), the Canadian high Arctic (Hudson and Henry, 2009; Hill and Henry, 2011), the Swedish sub Arctic (Hallinger *et al.*, 2010; Rundqvist *et al.*, 2011; Hedenås *et al.*, 2011), and the northwestern Russian Arctic(Macias-Fauria *et al.*,2012 ; Forbes *et al.*, 2010). Changes in growth of shrubs have varied from dramatic, i.e. 200% area increase in study plots (Rundqvist *et al.*, 2011) in sub arctic Sweden to early invasion of a fell field community on west Greenland plots by low shrubs (Callaghan *et al.*, 2011a). Structural changes within the tundra zone can result when low erect shrubs (e.g. *Salix*, *Alnus* spp.) increase significantly in height *in situ*. There is strong evidence that this has occurred in the past in Beringia (Edwards *et al.*, 2005) and is in progress now in the northwestern Russian Arctic (Macias-Fauria *et al.*, 2012).

Changes in species diversity could not be detected in the long-term study from Ellesmere Island in Canada (Hudson and Henry, 2009; Hill and Henry, 2011). However, other multi-decadal studies (see references in Callaghan and Tweedie, 2011) show small changes in plant community composition at sites in Canada, Greenland and Sweden that

indicate responses to warming and drying. Furthermore, aspen tree invasion has been recorded at a sub Arctic tree line (Van Bogaert *et al*., 2010).

Snow bed habitats have decreased in sub arctic Sweden (Björk and Molau, 2007; Hedenås *et al*., 2011). In other plant communities, changes have been less dramatic, ranging from small increases in species richness in the south west Yukon of the Canadian sub Arctic (Danby *et al*., 2011), through subtle changes in plant community composition in west and southeast Greenland (Daniëls and De Molenaar, 2011; Callaghan *et al*., 2011a) to 70 year stability of a plant community on Svalbard (Prach *et al*., 2010).

Early experimental studies projected that mosses and lichens would be disadvantaged by climate warming (Cornelissen *et al*., 2001; Van Wijk *et al*., 2004). Lang et al. (2012) showed that Arctic warming on two continents had consistent negative effects on lichen diversity and mixed effects on bryophyte diversity and Tømmervik et al. (2009) documented a significant decrease in lichens in northern Norway in the period 1957-2000 and a slight increase again in the period 2000-2006. Hudson and Henry (2009) reported significant increases in bryophyte biomass between 1981 and 2008 on Ellesmere Island. In contrast, moss communities on Iceland were stable during experimental summer warming and growth (Jonsdottir et al. 2005) and photosynthetic activity of a bryophyte was significantly reduced by simulation of acute mid-winter warming events in a sub-Arctic heath (Bjerke *et al*., 2011). Although significant recovery of lichens has been recorded recently in Finnmarksvidda (Tømmervik *et al*., 2012), Forbes and Kumpula (2009) recorded long-term and widespread lichen degradation in northern Finland attributed more to trampling of dry lichens by reindeer in summer than winter consumption as forage. Lichens, unlike bryophytes, were unaffected by extreme warm events in winter in the sub Arctic (Bjerke *et al*., 2011).

A meta-analysis (11 sites: (Walker *et al*., 2006) and a synthesis (61 sites: (Elmendorf *et al*., 2012a) of experimental warming studies of up to 20 years duration in tundra sites worldwide, showed, overall, increased growth of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness. Elmendorf et al. (2012a) point out that the groups that increased most in abundance under simulated warming were graminoids in cold regions and primarily shrubs in warm regions of the tundra. However, strong heterogeneity in responses to the experimental warming suggested that other factors could moderate the effects of climate warming significantly like herbivory, differences in soil nutrients and pH, precipitation, winter temperatures and snow cover, and species composition and density. Intersite comparisons indicated an association between the degree of summer warming and change in vascular plant abundance, with shrubs, forbs and rushes increasing with warming. However, the association was dependent on the climate zone, the moisture regime and the presence of permafrost.

28.2.3.3. Changes in Tree Line

Palaeorecords of vegetation change indicate that the northern tree line should extend upwards and northwards during current climate warming (IPCC FAR) because tree line is related to summer warmth (e.g. (Harsch *et al*., 2009). Although the tree line has moved northwards and upwards in many Arctic areas, there is *high confidence* that the tree line has not shown a general circumpolar expansion in recent decades. The existing evidence suggests varying patterns of re-location resulting from several co-occurring drivers.

An expansion of the tree line as a response to warming has been observed in many areas e.g. (Chapin III, 2005; Lloyd, 2005; Shiyatov *et al*., 2007; Kullman and Öberg, 2009) but in some areas, the location of the tree line has not changed or has changed very slowly (Masek, 2001; Holtmeier *et al*., 2003; Payette, 2007; MacDonald *et al*., 2008). A global study by Harsch et al. (2009) showed that only 52% of all 166 global tree line sites had advanced over the past 100 years. In many cases the tree line has even retreated (Vlassova, 2002; Dalen and Hofgaard, 2005; Kullman, 2005; Cherosov *et al*., 2010).

This diversity of response is also seen at the small scale. Within one area undergoing the same degree of climate warming (sub arctic Sweden and Siberian taiga), the tree line has shown increase, decrease and stability in neighboring locations (Van Bogaert *et al*., 2011; Lloyd *et al*., 2011). These variable responses clash with process-

based understanding in model projections and relate to local drivers of change that interact with or negate direct effects of climate warming (see below).

Model projections that suggest a displacement of between 11 and 50% of tundra by forest by 2100 (see references in Callaghan et al 2005) and shifts upslope by 2 to 6 m per year (Moen *et al*., 2004) and northwards by 7.4–20 km per year (Kaplan and New, 2006) might be overestimating rate of tree line advance by a factor of up to 2000 (Van Bogaert *et al*., 2011). The fastest upslope shifts of tree lines recorded during 20th century warming are in the range of 1 to 2 m year (Shiyatov *et al*., 2007; Kullman and Öberg, 2009) whereas the fastest so-far recorded northward-migrating tree line replaces tundra by taiga at a rate of 3–10 m year (Kharuk *et al*., 2006).

Evidence for densification of the forest at the sub Arctic tree line is robust and consistent within Fennoscandia (Tømmervik *et al*., 2009; Rundqvist *et al*., 2011; Hedenås *et al*., 2011) and Canada (Danby and Hik, 2007). Dendroecological studies indicated enhanced conifer recruitment during the twentieth century in the northern part of the Siberian taiga (Briffa *et al*., 2008) and tree growth was well correlated with warm summer temperature (Macdonald *et al*., 2008; Lloyd *et al*., 2011; MacDonald et al. 2008). Some of the changes are dramatic, such as an increase in area of mountain birch in study plots in northern Sweden by 600% between 1977/8 and 2009/10 (Rundqvist *et al*., 2011) and a doubling of tree biomass in Finnmarksvidda in northern Norway since 1957 (Tømmervik *et al*., 2009). Also, in at least one location, a tree species not present in 1977 has invaded the tree line (Van Bogaert *et al*., 2010; Rundqvist *et al*., 2011). However, model projections of displacement of deciduous forest by evergreen forest (Wolf *et al*., 2008; Wramneby *et al*., 2010) have not so far been validated.

Even where the mountain birch tree line has increased in elevation and shrub (e.g. willow, dwarf birch) abundance has increased, the response can be an interaction between climate warming, herbivory pressure and earlier land use (Olofsson *et al*., 2009; Hofgaard *et al*., 2010; Van Bogaert *et al*., 2011). There is evidence from Fennoscandia and Greenland that heavy grazing by large herbivores may significantly check deciduous low erect shrub (e.g. dwarf birch) growth (Post *et al*., 2008; Kitti *et al*., 2009; Olofsson *et al*., 2009). However, in cases where tall willow shrubs are already above the reindeer browse line of ≈1.8 m, their transformation into tree size individuals is likely to track warming temperatures rather than grazing intensity (Macias-Fauria *et al*.,2012 ; Forbes *et al*., 2010).

Climate warming might also have negative impacts on northern forests where growth is largely made possible by moisture supplied from melting of the winter snowpack (Yarie, 2008). In most of the boreal forest region, temperature increases have made the snow-accumulation season shorter, particularly in spring, and the warm season longer(Callaghan *et al*., 2011c), so that less of the annual water budget is from the spring pulse of snowmelt. Less moisture from snow and more rain now favors broadleaf trees over conifers and mosses in some areas (Juday, 2009) while moisture deficits are reducing the growth of some northern forests (Goetz *et al*., 2005; Verbyla, 2008) and making them more susceptible to insect pest outbreaks (see references in (Callaghan *et al*., 2011c)). Death of trees through drought stress or insect pest activity will increase the probability of fire that will have positive feedbacks on the climate from reduced carbon dioxide uptake, increased carbon dioxide loss from soils and decreased albedo as in tundra fires (Mack et al., 2011). There is evidence that recent warming in combination with snow anomalies has caused increased drought stress and insect damage to northern forests (see references in Callaghan et al. 2011c).

28.2.3.4. Changes in Animal Population Cycles

High-amplitude population cycles of herbivores like lemmings, voles, snowshoe hares and forest Lepidoptera (caterpillars of moths and butterflies) are characteristic processes of tundra and boreal forest ecosystems, influencing considerably the dynamics of vegetation and other animal populations in these ecosystems (Rydgren *et al*., 2007; Ims *et al*., 2007; Berg *et al*., 2008; Gilg *et al*., 2009; Krebs, 2011; Olofsson *et al*., 2012; Kausrud et al. 2009;).

The documented collapse or dampening of population cycles of voles and lemmings over the last 20-30 years in parts of Fennoscandia and Greenland (Scmidt et al. 2012), can be attributed with *high confidence* to climate change (Ims *et al*., 2007; Gilg *et al*., 2009; Ims *et al*., 2011; Kausrud et al. 2009). A shortening of the snow season and more thaw and/or rain events during the winter season have the potential to increase overall mortality and decrease winter reproduction because snow hardness increases and influence on the subnivean space which provides thermal

insulation, access to food, and protection from predators to high latitude rodents (Berg *et al*., 2008; Johansson *et al*., 2011; Kausrud et al. 2009).However, the causes of the changes in the lemming and vole cycles are still being debated as other factors than climate change may also be of importance(Brommer *et al*., 2010; Krebs, 2011).

Both the boreal forest and the mountain birch forest of Fennoscandia are regularly subject to large-scale tree mortality from insect outbreaks. Climate-mediated range expansion both in altitude and latitude of insect pests, and increased survival due to higher winter temperatures, has been documented for bark beetles in North America (Robertson *et al*., 2009; ACIA 2005) and for geometrid moths in Fennoscandia (Jepsen *et al*., 2008; Callaghan *et al*., 2010; Jepsen *et al*., 2011), causing more extensive forest damage than before. Outbreaks of insect pests like geometrid moths may even be of a magnitude that reduces the strengths of CO_2 sinks in some areas (Heliasz *et al*., 2011).

The latitudinal and altitudinal expansion of the range of the red fox (*Vulpes vulpes*) into the tundra and alpine areas is likely to be a response to warming which has strengthened interspecific competition with the much smaller arctic fox (*Alopex lagopus*) and most likely has contributed to the decline of this species and its population cycles in many Arctic regions (Fuglei and Ims, 2008; Henden *et al*., 2010; Killengren et al. 2007).

28.2.3.5. Changes in Reindeer and Muskox Populations

The decline in wild reindeer and caribou (both *Rangifer tarandus*) populations in certain regions of about 30 percent over the last 10-15 years have been linked both to climate warming and anthropogenic landscape changes (Post et al. 2009; Vors and Boyce 2009; Russell and Gunn 2010). Even though most of the Arctic has warmed, the decline in the populations has not been uniform. Some of the North American large herds have for example declined by 75-90 percent, while other wild herds there and semi-domestic herds in Fennoscandia and Russia have been stable or even increased (Gunn et al. 2009; Vors and Boyce 2009; Joly et al. 2011; Forbes et al. 2009; Forbes 2010; Kumpula et al. 2012).

A trophic mismatch causing increased calf mortality and drop in female productivity has been documented when timing of parturition in a population of caribou in Greenland did not keep pace with advancement of the plant-growing season and peak forage availability and quality caused by a warmer climate (Post and Forchhammer, 2008; Post *et al*., 2009a; Post *et al*., 2009b). It is suggested that similar warming-induced trophic mismatches have a role in the decline of circumpolar reindeer and caribou populations (Post et al. 2009a). This trophical mismatch has, however, been disputed as well as their extension of their study in Greenland to circumpolar populations (Griffith *et al*., 2010).

The increased primary productivity of Arctic tundra (see above) may potentially increase the supply of food for Arctic ungulates, although new biomass already above the browse would be inaccessible and therefore superfluous (Forbes *et al*., 2010). The overall quality of forage may decline during warming, for example if the nitrogen content of key fodder species for ungulates were to drop during warming (Turunen *et al*., 2009; Heggberget et al. 2010). As mentioned above, there are indications that lichen biomass, and important winter fodder for reindeer, is decreasing over much of the Arctic region. Arctic lichens have been shown experimentally to be vulnerable to icing events (Bjerke *et al*., 2011). Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes on the ungulate populations (van Der Wal *et al*., 2007; Turunen *et al*., 2009).

More frequent icing events and thicker snow-packs caused by warmer winters and increased precipitation may restrict access to vegetation and have profound negative influences on the population dynamics of Arctic ungulates (Berg *et al*., 2008; Forchhammer *et al*., 2008; Miller and Barry, 2009; Stien *et al*., 2010; Hansen *et al*., 2011; Stien et al. 2012). Behavioural plasticity may partly buffer such icing events (Hansen et al. 2010). In contrast, warmer winters were shown to enhance the abundance of reindeer in a population in Svalbard because access to vegetation became easier (Tyler *et al*., 2008), and ice on the grazing areas was not the main reason in 31 declines of 12 different reindeer and caribou populations (Tyler, 2010). Over the period 1970 to 2006, reindeer calf production in Finland increased by almost one calf per 100 females for each day of earlier snow melt (Turunen *et al*., 2009). More frequent icing events have caused heavy mortality in domestic reindeer herds (Forbes et al. 2009) and some of the herders in Yamal in Siberia have lost as much as 25% of the herds in one winter season due to icing (Bartsch et al.

2010). Despite this, the indigenous Nenets inhabiting the area, stressed hydrocarbon development as the main long-term threat to their existence (Forbes and Stammler 2009; Forbes et al. 2009; Kumpula et al. 2012).

28.2.3.6. Long-Term Trends and Event-Driven Changes in Ecosystems

Changes in vegetation and animal populations are driven relatively slowly by long-term climate change but tipping points may be reached quickly by events such as extreme weather, fire, insect pest and disease outbreaks. While the impacts of winter thaw events are well-documented for animals (see above), the severe impacts of tundra fires on vegetation and biospheric feedbacks have been described only recently (Mack *et al*., 2011). Similarly, experimental and observational determinations of the impacts of extreme winter thaw events on plants, soil arthropods and ecosystem processes have become evident since IPCC 2007 (e.g.(Bokhorst *et al*., 2011)). For example, results from experimental thaws during winter were validated by a natural thaw in northern Norway and Sweden in 2007 that reduced NDVI by almost 30% over an area of at least 1400 km^2 (Bokhorst *et al*., 2009). Studies on relationships between climate change and plant disease are almost totally lacking but a new study demonstrated the effect of increased snow accumulation on a higher incidence of fungal growth on sub Arctic vegetation (Olofsson *et al*., 2011).

28.2.3.7. Antarctic Terrestrial Systems

Climate change will impact Antarctic terrestrial habitats in all three biogeographic regions through changes in air temperature, wind speed, precipitation (rain and snowfall), permafrost and exposure of new habitat through glacial/ice retreat. There are no documented trends in changing surface areas of different habitats or in the exposure of new habitat, a major gap in this assessment.

Few robust studies of biological responses to observed climatic changes in natural Antarctic terrestrial ecosystems are available. Most attention has been given to rapid population expansion and local-scale colonisation by the two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in the maritime Antarctic (Parnikoza *et al*., 2009; Convey *et al*., 2011), which remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. Radiocarbon techniques are now also demonstrating long-term biological effects of Antarctic climate change on moss beds (Clarke *et al*., 2012). One important aspect underlying these changes is thought to be that air temperatures have increased past the critical temperature at which successful sexual reproduction (seed set) can now take place, changing both the dominant mode of reproduction, and increasing the potential distance for dispersal. Similar changes in the local distribution and development of typical cryptogamic vegetation of this region have been reported (Convey, 2011), including the rapid colonisation of ice free ground made available through glacial retreat and reduction in extent or previously permanent snow cover (Olech and Chwedorzewska, 2011). As these vegetation changes creates new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonises them. Such hypotheses remain to be confirmed through the establishment of robust baseline survey and monitoring studies (Convey, 2006; Convey, 2010), which are now an urgent priority (Wall *et al*., 2011). A critical part of such studies will be to link well-described large-scale climatic trends with that of microclimates experienced by terrestrial biota at much smaller and relevant physical scales (Turner *et al*., 2009).

28.2.4. Human Populations

Although humans have been present in the Arctic for thousands of years, Antarctica has no permanent human settlements; instead, only temporary residents who are either visiting scientists or staff at research facilities. Therefore, this Human Populations Section assesses the risks and impacts of Arctic warming on the diverse human communities across the Arctic where people have been addressing change for centuries. While it is recognized that several large industrial Arctic cities in Russia and elsewhere have serious climate change-related challenges, this section focuses on indigenous, isolated, and rural populations because they are especially vulnerable to climate change due to their dependence on the environment for food, culture, transportation, security, and ultimate survival;

their political and economic marginalization; and existing social, health, poverty, and other disparities. (Larsen *et al*., 2010; [AR5 12.3]) In addition, a large amount of literature documenting the impacts of climate change on the health and well-being of Arctic indigenous residents has been published since the last report.

The warming Arctic and the significant changes in the cryosphere are impacting residents across the region through a complex set of physical, environmental, cultural, economic, political, and socio-cultural factors operating on and within Arctic communities, which have important implications for the health and well-being of all Arctic populations. These influences are expected to vary significantly among the highly diverse communities which range from small, remote, predominantly indigenous to large northern, industrial settlements. (Larsen and Fondahl, 2010) It is estimated that there are between 4 and 9 million people living in the Arctic depending upon geographic delineation of Arctic which includes original residents (indigenous peoples) as well as a broad spectrum of more recent settlers ranging from subsistence hunters to oil industry personnel to urban office workers, scientists, military, and tourists. (Hovelsrud *et al*., 2011) Approximately two-thirds of Arctic people live in relatively large settlements of over 5,000 residents, the other one-third is scattered in small and often very remote, isolated communities. (Bogoyavlensky and Siggner, 2004; Larsen and Fondahl, 2010) During the past century, the composition of Arctic communities and settlements has been shifting dramatically due to seasonal and permanent immigration into the Arctic driven by the development of resources such as oil and gas, fishing, and mineral resources or the necessity to escape problems in homelands outside the Arctic, including some population declines from 2000 to 2005, especially in Russia. (Hovelsrud et al, 2011)

Climate change and globalization, environmental contamination, resource development, plus the new activities and residents competing for lands and resources traditionally used by Indigenous peoples, are especially impacting the Indigenous populations of the North and are projected to increase in the future. (Abryutina, 2009; Larsen *et al*., 2010). The estimated indigenous populations in the Arctic are between 400,000 and 1.3 million. (Hovelsrud et al, 2011) Approximate numbers of Indigenous residents are: Canada, 66,000; Denmark, Greenland, 50,000; Norway, Sweden, and Finland, 50,000; Russia, 90,000; and USA, 110,000 (Galloway McLean, 2010) The percent of the populations of indigenous peoples in the Arctic range from 3-4 % in Russia to 80% in Greenland. (Galloway McLean, 2010) Indigenous peoples have been sustained by the region's terrestrial, marine and freshwater renewable resources, including mammals, birds, reindeer, fish and plants for sustenance, cultural, religious, economic, medicinal, and community health for many generations. (Nuttall *et al*., 2005; Parkinson, 2009) However, the ability of Indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, fishing, and herding is increasingly being threatened by climate change and associated multiple stressors.

Human health and well-being may be defined as the mental, physical, spiritual, and social well-being plus the absence of disease and infirmity, and includes cultural and social practices as critical contributing factors. (Larsen and Huskey, 2010) To fully understand the potential for projected impacts of climate change on the health and well-being of the diverse communities in the Arctic, it is necessary to take into account a complex suite of underlying interconnected factors including not only additional stressors such as contaminants like POPs (persistent organic pollutants), radioactivity, and heavy metals such as mercury, but also the complicated social, cultural, political, and economic forces operating in these communities such as persistent poverty and lack of health and other services. (Abryutina, 2009; Ford and Furgal, 2009; Larsen and Huskey, 2010; AMAP, 2009; UNEP/AMAP, 2011) Climate change alone is not always the most important factor determining vulnerability in polar communities, but it can be a force that exacerbates other stresses. (Ford *et al*., 2010) A significant amount of research has been carried out on the health and well-being of Arctic indigenous populations and, therefore, this section emphasizes both the direct and indirect impacts of climate changes on these more vulnerable segments of the population.

28.2.4.1. Direct Impacts of a Changing Climate on the Health of Arctic Residents

Direct impacts of climate changes on the health of Arctic residents include extreme weather events, rapidly changing weather conditions, and increasingly unsafe hunting conditions (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts). (IPCC Special Report: Managing Risk of Extreme Events, 2012; AMAP, 2009) Intense precipitation events and rapid snowmelt are

expected to impact the magnitude and frequency of slumping and active layer detachment resulting in rock falls, debris flow, and avalanches. (Kokelj *et al*., 2009; Ford *et al*., 2010) Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration and/or rapid onset of extreme weather events and storms, which, in turn, may create risks to safe travel or subsistence activities, loss of access to critical supplies and services to rural or isolated communities (e.g., food, fuel, telecommunications), and risk of being trapped outside one's own community. (Laidre *et al*., 2008; Brubaker *et al*., 2011b). Changing river and sea ice conditions affect the safety of travel for indigenous populations especially, and inhibit access to critical hunting, herding and fishing areas. (Andrachuk and Pearce, 2010; Derksen *et al*., 2012) For example, reductions in land-fast ice plus increased open water area cause less predictable fog and sea-ice conditions, creating treacherous coastal travel conditions and more difficult communications among communities. (Barber *et al*., 2008)

Cold exposure has been shown to increase the frequency of certain injuries (e.g. hypothermia, frostbite) or accidents, and diseases (respiratory, circulatory, cardiovascular, musculoskeletal skin). (Revich and Shaposhmikov, 2010) Studies in Northern Russia have indicated an association between low temperatures and social stress and cases of cardiomyopathy, a weakening of the heart muscle or change in heart muscle structure. (Revich and Shaposhnikov, 2010) It is estimated that 2,000 to 3,000 deaths/yr occur from cold-related injury and diseases during the cold season in Finland. Respiratory diseases among children in Northern Russia are 1.5 to 2 times greater than the national average. It is expected that winter warming in the Arctic will reduce winter mortality rates, primarily through a reduction in respiratory and cardiovascular deaths (Shaposhnikov *et al*., 2010). It is also believed that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, some Arctic residents are reporting respiratory and cardio stress associated with extreme warm summer days which has not previously been experienced. (Revich and Shaposhnikov, 2010).

28.2.4.2. Indirect Impacts of Climate Change on the Health of Arctic Residents

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), the built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion). (Maynard and Conway, 2007; Brubaker *et al*., 2011a; Parkinson and Evengard, 2009). Local and traditional knowledge in communities across the Arctic are observing extremes not previously experienced and increasingly unusual environmental conditions (e.g., (Laidler *et al*., 2009; Ignatowski and Rosales, 2012)). There also appears to be an increase in injuries related to climate changes among residents of northern communities associated with 'strange' or different environmental conditions, such as earlier break-up and thinning of sea ice. (Ford and Pearce, 2010) These climate-driven disruptions in the physical environment are increasingly being shown to cause a variety of serious mental and psychological conditions in many Arctic communities, particularly in vulnerable, already disadvantaged populations. (AR5 Chapter 11; Portier et al, 2010; USARC, 2010)

Underlying all climate change impacts and processes, are the complicated impacts from contaminants such as POPs (persistent organic pollutants), radioactivity, and heavy metals (e.g., mercury) which create additional and/or synergistic impacts on the overall health and well-being of the communities. (UNEP/AMAP, 2011) Contaminants and human health in the Arctic are tightly linked to the climate and Arctic ecosystems by factors such as contaminant cycling and climate (increased transport to and from the Arctic), exposure to contaminants, the risk of infectious diseases in Arctic organisms, and the related increased risks of transmission to residents through subsistence life ways, especially indigenous peoples. (AMAP, 2010; UNEP/AMAP 2011) The consumption of traditional foods by indigenous peoples places these populations at the top of the Arctic food chain and through biomagnification, therefore, they may receive some of the highest exposures in the world to certain contaminants. (UNEP/AMAP, 2011) These contaminants such as POPs are known for their adverse neurological and medical effects on humans, particularly, the developing fetus, children, women of reproductive age and the elderly. Thus, contaminants must be a significant part of any climate impact assessment as their potential health effects include

serious conditions such as nervous system and brain development problems, interference with hormones and sexual development, weakened immune systems, organ damage, cardiovascular disease and cancer. (UNEP/AMAP, 2011)

There are additional concerns regarding radioactivity and climate change because contamination can remain for long periods of time in soils and some vegetation, and because the terrestrial environment can create high exposures for people. (AMAP, 2010) Furthermore, climate changes not only have the ability to mobilize radionuclides throughout the Arctic environment, but can also potentially impact infrastructure associated with nuclear activities by changes in permafrost, precipitation, erosion, and extreme weather events. (AMAP, 2010) Additionally, there is a very high density of potential and existing radionuclide sources in some parts of the Russian Arctic and the risk for accidents is a significant cause for concern. (AMAP, 2010)

Warming temperatures are enabling increased overwintering survival and distribution of new insects that sting and bite as well as many bird and insect species that can serve as disease vectors and, in turn, causing an increase in human exposure to new and emerging infectious diseases. (Parkinson *et al*., 2008; Epstein and Ferber, 2011). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia and Canada (Ogden *et al*., 2010; Tokarevich *et al*., 2011) and Sweden (Lindgren and Gustafson, 2001), *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean. (Hughes-Hanks *et al*., 2005) It is also expected that temperature increases will increase the incidence of zoonotic diseases that can be transmitted to humans. (Revich *et al*., 2012) Many Arctic zoonotic diseases which currently exist in local host species (e.g., tularemia in rabbits, muskrats and beaver, and rabies in foxes) can spread through climate-related mechanisms such as relocation of animal populations. (Revich et al, 2012;)

Harmful algal blooms (HABs), are increasing globally and are known to be influenced directly by climate change related factors such as temperature, winds, currents, nutrients and runoff. (Portier *et al*., 2010) These HABs contain biotoxins with significant neurotoxic effects and can be a serious health hazard to humans or animals (paralysis, death) when the toxin is ingested through seafood, direct contact, or sea spray aerosols. (Portier *et al*., 2010; Epstein and Ferber, 2011). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, Vibrio parahaemolyticusin, in Alaskan oysters (McLaughlin *et al*., 2005). Finally, there are concerns that the warmer temperatures may raise the possibility of anthrax exposure in Siberia from permafrost thawing of historic cattle burial grounds. (Revich and Podolnaya, 2011)

The impacts of climate change on food security and basic nutrition are critical to human health because subsistence foods from the local environment provide Arctic residents, especially, indigenous peoples, with unique cultural and economic benefits necessary to well-being and contribute a significant proportion of daily requirements of nutrition, vitamins and essential elements to the diet (Ford and Berrang-Ford, 2009; Ford, 2009). However, climate change is already posing an important threat to food security and safety for indigenous peoples and the availability of country food because of the impacts on traditional subsistence hunting, fishing and herding. (Ford *et al*., 2010) The decrease in predictability of weather patterns as well as low water levels and streams, timing of snow, ice extent and stability are impacting the possibilities for successful hunting, fishing and access to food sources and increasing the probability of accidents. (Ford and Furgal, 2009) Populations of marine and land mammals, fish and water fowl are also being reduced or displaced by changing temperatures, ice state, habitats and migration patterns reducing the traditional food supply. (Gearheard *et al*., 2006; West and Hovelsrud, 2010)

Furthermore, traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by warming temperatures, thus reducing food available to the community. (Brubaker *et al*., 2011b) For example, food contamination problems are becoming important wherever thawing of permafrost "ice cellars" is occurring for communities and families and increasingly wet conditions make it harder to dry food for storage. (Hovelsrud *et al*., 2011) These reductions in the availability of traditional foods plus general globalization pressures are forcing indigenous communities to increasingly depend upon expensive, non-traditional and often less healthy western foods, increasing the rates of modern diseases associated with processed food, such as cardiovascular diseases, diabetes, dental cavities, and obesity. (Berrang-Ford *et al*., 2011; Brubaker *et al*., 2011b) A complicating factor in evaluating trade-offs between traditional and market food is that wild foods – especially those at the top of the food chain - represent the most significant source of exposure to environmental contaminants. (AMAP, 2011)

Climate change is beginning to threaten community and public health infrastructure, often in communities with no central water supply and treatment sources. This is especially serious in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada) through increased river and coastal flooding and erosion, increased drought and thawing of permafrost, resulting in loss of reservoirs, damage to landfill sites, or sewage contamination. (GAO, 2009) Salt-water intrusion and bacterial contamination may also be threatening community water supplies. (Parkinson *et al.*, 2008; Virginia and Yalowitz, 2012) Quantities of water available for drinking, basic hygiene, and cooking are becoming limited due to damaged infrastructure, drought, and changes in hydrology. (Virginia and Yalowitz, 2012) Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure such as sewage lagoons or inadequate hygiene, spreads sewage in villages where the majority of homes have lower water availability because of no in-house piped water source. This, in turn, can result in higher rates of hospitalization for pneumonia, influenza, and respiratory viral infections. (Parkinson and Evengard, 2009) This suggests that reduced water availability because of climate change impacts may result in increase rates of hospitalization among children for respiratory infections, pneumonia, and skin infection.(Parkinson *et al.*, 2008; Virginia and Yalowitz, 2012)

Finally, it is now well-documented that the many climate-related impacts on Arctic communities are causing significant psychological and mental distress and anxiety among the residents. (Portier *et al.*, 2010; Coyle and Susteren, 2012; AR5 Chapter 11; Levintova, 2010) The changes in the physical environment which threaten certain communities (e.g., through thawing permafrost and erosion) and which may lead to forced or voluntary relocation of residents or changes or declines in resources resulting in reduced access to subsistence species are often a pathway to rapid and long-term cultural change including loss of traditions. (Galloway-MacLean, K., 2010) These types of losses are, in turn, causing mental health impacts among indigenous and other vulnerable, isolated populations. (Curtis *et al.*, 2005; Albrecht *et al.*, 2007; Coyle and Susteren, 2012) Psychological impacts are especially acute for individuals and communities who feel intimately connected with the environment and those experiencing cumulative effects from repeated impacts such as natural disasters and extreme weather. (Portier *et al.*, 2010; AR5) A specific psychological condition called “solastalgia”- a strong feeling of loss and dislocation when people feel that changes to their environment are harmful - is becoming more common globally. (Albrecht *et al.*, 2007; Portier *et al.*, 2010) Special concern has been expressed by many communities concerning the unusually high and increasing numbers of suicides in the Arctic especially among indigenous youth, and efforts are under way to try to develop a thorough assessment as well as establish effective intervention efforts. (Albrecht *et al.*, 2007; Portier *et al.*, 2010; USARC, 2010)

28.2.5. Economic Sectors

Economic activity takes place in both of the Polar Regions. In the Arctic, economic sectors are confronted with multiple stressors of which climate change is just one (Larsen, 2010; Forbes, 2011; Hovelsrud *et al.*, 2011).

The Arctic economy consists of a combination of formal and informal sectors. Formal and market-based economic activity is projected to have both costs and benefits, with some commercial activities becoming more profitable while others will face decline. Outside of the urban areas indigenous and non-indigenous peoples often mix activities of the formal sector (e.g. commercial fish harvesting, oil and mineral resource extraction, forestry, and tourism) with traditional or subsistence activities, which include harvesting a variety of natural renewable resources to provide for human consumption. Hunting and herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Nuttall *et al.*, 2005; Poppel and Kruse, 2009; Larsen and Huskey, 2010; Crate *et al.*, 2010; Poppel 2006; Aslaksen et al 2009). Significant impacts on the ability of key subsistence marine and terrestrial species are being observed and are expected to continue as climate continues to change, and the ability to maintain one’s economic well-being may be affected. In the early 1990s – initially in western Canada, and later elsewhere - indigenous communities started reporting climate change impacts (Berkes and Armitage, 2010). According to some herders, whalers and walrus hunters non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes and Stammler, 2009; Ignatowski and Rosales, 2012; Forbes et al. 2009; www.Aksik.org).

In the Antarctic, economic activities include fisheries and tourism. Commercial mining activity does not take place in Antarctica, and fisheries remain the only large-scale resource exploitation activity.

28.2.5.1. Arctic

28.2.5.1.1. Agriculture and forestry

Climate change is very likely to have positive impacts for agriculture, including extended growing season, although variations across regions are expected (Hovelsrud *et al.*, 2011). Tree limits in Iceland, for example, are now found at higher latitudes than before, and the productivity of many plants has increased (Björnsson et al, 2011). Climate change is likely to have economic costs and benefits for forestry (e.g. Aaheim, et al. 2009). The accessibility to logging sites is (an already observed) concern for the forestry industry. There is an observed vulnerability of forestry to changes that affect the condition of roads and thus accessibility during thawing periods (Keskitalo, 2008). Grain production in Iceland has increased in the last two decades, and work on soil conservation and forestry has benefited from warming (Björnsson et al, 2011). Agricultural opportunities in the Arctic are likely to expand because of a warmer climate, but are likely to remain of minor importance to the Arctic economy (Eskeland and Flottorp 2006). In areas with a reduction in snow cover, the growing season may be extended (Grønlund, 2009; Falloon and Betts, 2009; Tholstrup and Rasmussen 2009).

Climate change is very likely to have costs and benefits for agriculture and forestry (*high confidence*).

28.2.5.1.2. Open water fisheries

The impacts of climate change will occur within the context of other anthropogenic activities including commercial fishing. Fish stocks have been exploited for centuries in the polar region (Geffen *et al.*, 2011). Commercial fisheries in the polar region of the northern hemisphere are sharply divided between regions of high yield and commercial value such as the southern Bering Sea, Baffin Bay, the east and west Greenland Seas, the Iceland Shelf Sea, the deep Norwegian/Greenland Sea, and the Barents Seas and low volume subsistence fisheries in the coastal regions of the Arctic Ocean (Figure 28-4).

[INSERT FIGURE 28-4 HERE
Figure 28-4: Fishing vessel activity. Source: AMSA, _____.]

In high yield regions, complex management strategies have been developed to build sustainable fisheries and rebuild overfished stocks (Froese and Proelß, 2010; Hollowed *et al.*, 2011; Livingston *et al.*, 2011). The performance of these strategies relative to the goal of preventing overfishing and rebuilding overfished stocks differs by region for a variety of reasons including: data quality, enforcement, management policies and strategies for community based management (Worm *et al.*, 2009; Hutchings *et al.*, 2010; Gutierrez *et al.*, 2011). Sustainable fishing practices are expected to continue in the future and may improve as managers strive to implement an ecosystem approach to management and overfished stocks are expected to rebuild (*medium confidence*). Successful spatial management of shared resources under shifting ocean conditions will require an understanding of the mechanisms underlying observed range shifts (Hannesson, 2013).

The relative absence of commercial fishing activity in the Arctic Ocean results from a combination of environmental policy, the abundance of the resource and infrastructure for capturing and processing fish. The remote location, difficulties in accessing fishing grounds especially during winter, and relatively low stock sizes all serve as deterrents to the development of commercial activities in the Arctic Ocean. In the Beaufort Sea, some evidence of range extensions of commercial species including Pacific cod and walleye pollock were observed in the Beaufort Sea (Rand, 2011). However, in the U.S. portion of the Chukchi Sea and Beaufort Sea, a recent analysis showed only three species were found in sufficient densities to support a modest commercial fishery: snow crab (*Chionoecetes opillio*), Polar cod (*Boreogadus saida*) and saffron cod (*Elegins gracilis*) (Stram and Evans, 2009; Wilson, 2009).

28.2.5.1.3. Freshwater fisheries

Several Arctic coastal fishes are targeted for subsistence and commercial use in the Arctic including: chum salmon (*Oncorhynchus keta*), Dolly varden (*Salvelinus malma*), Arctic char (*Salvelinus alpinus*), Arctic grayling (*Thymallus arcticus*) lease cisco (*Coregonus sardinella*) and Arctic cisco (*Coregonus autumnalis*). Commercial transactions from fishing are typically for local markets (Reist *et al*., 2006). The survival of Arctic coastal fishes depends on a complex suite of environmental conditions (Reist *et al*., 2006). Recent studies show that factors that influence the marine exit are critical for survival of salmon and cisco (Moulton et al. 2010; Mundy, 2011). Climate change related factors that influence the water level and freshening of rivers will influence run size of these species (Fechhelm et al 2007).

28.2.5.1.4. Marine transportation in the Arctic Ocean

Climate change is expected to lead to an increasingly ice free Arctic Ocean and increased navigability of Arctic marine waters. This is expected to bring economic opportunities to northern, more remote regions (e.g. (Prowse *et al*., 2009) Peters et al. 2011). New possibilities for shipping routes and extended use of existing routes may result from increased melting of sea ice (Paxian *et al*., 2010; Corbett *et al*., 2010; Khon *et al*., 2010; Peters et al., 2011). Observations and climate models indicate that in the period between 1979-1988 and 1998-2007 the number of days with ice free conditions (less than 15% ice concentration) increased by 22 days along the Northern Sea Route (NSR) in the Russian Arctic, and by 19 days in the North-West Passage (NWP) in the Canadian Arctic, while the average duration of the navigation season in the period 1980-1999 was 45 and 35 days, respectively (Mokhow and Khon, 2008).The increased shipping associated with the opening of the NSR will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific The frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season of natural resources, which is the late spring/summer. In this period, vulnerable natural resources are spread throughout the NSR area in the Arctic (Østreng 2006), which may negatively affect the future status of marine, terrestrial and freshwater biota since there will be substantial coastal infrastructure to facilitate offshore developments (Meschtyb, N., Forbes, B., Kankaanpää,P., 2010). Coastal terrestrial and freshwater habitats are especially critical for maintaining the large reindeer herds managed by indigenous Nenets along the Barents and Kara seashores and the loss of access to these pastures and fishing lakes and rivers would likely have knock-on effects throughout the region (Kumpula *et al*., 2011; Forbes et al. 2009). Thus, the combined actual and potential socio-economic and social-ecological footprint of commercial shipping is likely to be significant (e.g. (Mikkelsen and Langhelle, 2008)). In the case of Svalbard, oil spills on have increased due to the growth in activities related to tourism and research. Dangers of a cruise ship or cargo ship running a ground and with subsequent oil spillage is the biggest environmental risk connected to marine transportation at Svalbard (NorAcia 2010). Peters et al. (2011) find by using a bottom-up shipping model and a detailed global energy market model to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050, that based on estimated sea-ice extent: there will be rapid growth in transit shipping; oil and gas production will be moving into locations requiring more ship transport; and this will lead to rapid growth in emissions from oil and gas transport by ship.

Increased economic opportunities along with challenges associated with culture, security and environment, are expected in Northern Canada with increased navigability of Arctic marine waters together with expansion of land- and fresh water-based transportation networks (Furgal C., 2008). Based on a study using four water level scenarios, a base case with only seasonal and annual variation in water levels and three climate change scenarios, results suggest that Great Lakes rivers will be impacted by climate change affecting both shipping and nonindigenous species due to expected lower water levels, shorter times of ice cover, and higher surface water temperatures (Millerd, 2007). An increase in the length of the summer shipping season, with sea-ice duration expected to be 10 days shorter by 2020 and 20-30 days shorter by 2080, is likely to be the most obvious impact of changing climate on Arctic marine transportation (Prowse *et al*., 2009). The reduction in sea ice and increased marine traffic could offer opportunities for economic diversification in new service sectors supporting marine shipping. These possibilities however also come with challenges including their predicted contribution to the largest change in contaminant movement into or within the Arctic, as well as their significant negative impacts on the traditional ways of life of

northern residents (Furgal C., 2008). Added shipping and economic activity will increase the amount of black carbon and reinforce warming trends in the region (Lack and Corbett 2012, Levitsky 2011), leading to additional economic activity. (Lack, D. A.; Corbett, J. J., 2012).

28.2.5.1.5. Infrastructure

Much of the physical infrastructure and the hunting activities in the Arctic rely on and are adapted to local sea-ice conditions, permafrost, snow and the seasonal and behavioral patterns of the harvested fish and animals, which will be affected by the changing sea-ice condition, rendering them especially climate sensitive (Huntington *et al*., 2007; Sundby and Nakken, 2008; West and Hovelsrud, 2010; Forbes, 2011) Martin et al. 2009; Sherman et al., 2009). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower poses major economic costs and risks, which are more closely linked to the design lifetime of the structure than with thawing permafrost. Still, current engineering practices are designed to help minimize the impacts (Prowse *et al*., 2009). Climatic and other large-scale changes have potentially large effects on Arctic communities, where relatively simple economies (depending heavily on resource extraction and subsidies) leave a narrower range of adaptive choices (Anisimov and Vaughan, 2007; Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford *et al*., 2010; Forbes, 2011; Berkes et al 2003).

In Northern Canada climate warming presents an additional challenge for northern development and infrastructure design. While the impacts of climate change become increasingly significant over the longer time scales, in the short term of greater significance will be the impacts associated with ground disturbance and construction (Prowse *et al*., 2009); Smith and Risebrough 2010).

28.2.5.1.6. Resource exploration

The Arctic has large reserves of minerals (Lindholt, 2006; Peters et al. 2011) and potentially large reserves of undiscovered sources of raw materials, and oil and gas. About one-fifth of the world's undiscovered oil and gas reserves are located within the Arctic region (Gautier *et al*., 2009). While oil and gas production has declined in some fields, there have been new discoveries in others (AMAP, 2010). Due to high costs and difficult access conditions, and despite future reductions in sea-ice, it is not clear that future oil and gas production in the Arctic will increase (Peters et al., 2011). Predicted new access to offshore energy resources is hypothesized to be a significant share of the global supply of oil and gas (Gautier *et al*., 2009; Berkman and Royal United Services Institute for Defence and Security Studies., 2010).The socio-economic impacts on the Arctic region and local communities of oil and gas exploration activity can be positive or negative (Duhaime *et al*., 2004; Huntington *et al*., 2007; Forbes, 2008; Kumpula *et al*., 2011)Forbes et al. 2009). Arctic resources will *likely* play a growing role in the world economy. At the same time, increased accessibility is expected to create challenges for extraction, transport, engineering, search-and-rescue needs and responses to accidents (Hovelsrud *et al*., 2011). Increased emissions due to rapid growth in Arctic Ocean transportation of oil and gas are projected (Peters et al. 2011).

About 50% of oil and gas production in the Arctic is oil; in Canada (59%), Alaska (87%), East Russia (9%), West Russia (46%), and in Norway (84%) (Peters et al., 2011). Projected declines in sea-ice covers leading to development of integrated land and marine transportation networks in Northern Canada, may stimulate further mine exploration and development (Prowse *et al*., 2009). Reduced sea ice extent is projected to lead to increased Arctic shipping of oil and gas with projections of increased future emissions of short-lived pollutants, ozone pre-cursors, and long-lived greenhouse gases (Peters et al., 2011)

28.2.5.1.7. Informal, subsistence-based economy

Inuit and Saami have expressed strong concern about how a rapidly warming climate will affect their livelihoods (Forbes and Stammler, 2009). For Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn, earlier melt-out and faster sea ice retreat in spring, and thinner, less predictable ice in general (Krupnik and

Jolly, 2002). Diminished sea ice translates into more difficult access for hunting marine mammals, and greater risk for the long-term viability of polar bear populations (Laidre *et al.*, 2008). Most Inuit communities depend to some extent on marine mammals for nutritional and cultural reasons, and many benefit economically from polar bear and narwhal hunting. A reduction in these resources represents a potentially significant economic loss (Hovelsrud *et al.*, 2008). Among Fennoscandian Saami, the economic viability of reindeer herding is threatened by competition with other land users coupled with strict agricultural norms (Forbes, 2006). Reindeer herders are concerned that more extreme weather may exacerbate this situation (Oskal et al., 2009).

Climate change is affecting the reindeer herding communities through greater variability in snow melt/freeze, ice, weather, winds, temperatures (especially warmer winters), and precipitation, which, in turn are affecting snow quality and quantity – the most critical environmental variables for reindeer sustainability (Magga *et al.*, 2011; Eira *et al.*, 2012). Reindeer must forage continually and any significant impediment to their ability to access the plants (e.g. lichens) under the snow cover each day can threaten their very survival (Kitti *et al.*, 2009; Magga *et al.*, 2011). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow which then block the animals' access to their forage and subsequent starvation (Maynard *et al.*, 2011; Eira *et al.*, 2012; Bongo *et al.*, 2012). Annual migration patterns between summer and winter pastures are being challenged due to changes in the freeze-thaw cycles of rivers and lakes, with spring thaws occurring earlier and soft ice no longer able to support the reindeer as they try to cross (Klein *et al.*, 2005; Abryutina, 2009; Vuojala-Magga *et al.*, 2011). Warmer Arctic temperatures have increased insect harassment causing major interference with foraging (Kitti *et al.*, 2006). Indirect climate change impacts are also occurring, which have major implications for reindeer pasture availability and migration routes. With the lack of land-fast ice along the Arctic coasts in recent years, longer summers, and intense pressure to develop oil, gas and minerals in the North, the Arctic regions are becoming far more accessible to humans and industrial development, resulting in additional sources of increasing and irreversible loss of pasturelands (Kitti *et al.*, 2006; Bongo *et al.*, 2012).

The increasing global demand for energy and mineral resources plus an aggressive development of oil and gas fields as well as mining of other resources are encouraging rapid development with its associated infrastructure, pipelines, drill pads, roads, and pollution all across the once-rich pasture lands of the reindeer seasonal migration routes. (Forbes and Stammler, 2009; Magga *et al.*, 2011) In many locations, the associated infrastructure is being built across migration routes in Northern Russia, often blocking pathways to seasonal pastures and eliminating camping and fishing site for herders (Rees *et al.*, 2008; Bongo *et al.*, 2012; Forbes et al, 2009; Kumpula et al. 2012).

28.2.5.2. Antarctica and the Southern Ocean

The primary economic activities that currently take place in Antarctica are fisheries and tourism. Scientific activity by a number of nations is also taking place and has the potential to impact upon local habitats and communities. Mineral resource activity is currently prohibited south of 60°S until at least 2048 under the Protocol on Environmental Protection to the Antarctic Treaty. All activities in the region are currently regulated under the governance regimes described in Section 28.2.7, unless sovereign activities in subantarctic territories are exempted from those regulations. Patterns of fisheries and tourism and the vulnerabilities of the ecosystems to these activities are likely to be affected by climate change (Kawaguchi *et al.*, 2009; Constable, 2011; Chown *et al.*, 2012).

28.2.5.2.1. Fisheries

Fisheries in Antarctica were reported in AR4. Further analyses since then have shown that the current fishery in the southwest Atlantic, if it were to take the Total Allowable Catch of 5.6 million tonnes, could amount to approximately 6% of existing marine capture fisheries; current catches have been between 100-200,000 tonnes but are now increasing (Nicol *et al.*, 2011). The pattern of the krill fishery has been affected by changes in the sea ice extent around the Antarctic Peninsula. In recent years, the fishery has been taking advantage of the ice-free conditions and taking more of its catch during winter in that region (Kawaguchi *et al.*, 2009) . This changing pattern in the krill fishery will need to be accounted for by CCAMLR in the management strategy for the fishery. Catch

levels are expected to be larger than at present but this will depend more on economic rather than environmental constraints in the short to medium term.

CCAMLR aims to develop an ecosystem-based feedback management procedure for krill fisheries based on indicators of the status of krill and its predators (Constable 2011). This work has not yet factored in measures to account for climate change impacts on the ecosystem, including whether the ecosystem effects of climate change can be differentiated from the effects of fishing (Trathan and Agnew, 2010; Constable, 2011).

28.2.5.2.2. Tourism

Ship-based tourism is a significant industry in Antarctica. The large majority of tourists visit Antarctica aboard ships, and the industry does not involve permanent shore-based infrastructure. Over recent decades, the number of tourists visiting Antarctica has risen, with tourist numbers landing on shore having increased from 7322 in 1996/1997 to 32,637 in 2007/2008 , with one of the busiest sites being at Goudier Island to the west of the Antarctic Peninsula experiencing at least half of the visits (IAATO 2012). Tourists visit Antarctica in order to view scenery, wildlife, and historic sites, and to experience wilderness. As the numbers of tourists have increased, concerns have been expressed about the potential disturbance caused by visitors, e.g. visitors approaching too close to wildlife either on foot or by cruising in small boats. Risks exist of accidental pollution from maritime accidents (a number of groundings and one foundering are recorded), although no significant pollution incidents have occurred in recent decades. Tourism activity is expected to continue to increase, and as more ice-free areas become available as a result of climate change, there is an increasing likelihood of the introductions of alien species to terrestrial environments from tourism and other vectors (Chown, Lee et al. 2012). A combination of mandatory and voluntary management measures are in place under the Antarctic Treaty's Protocol on Environmental Protection (the Protocol) and measures of the Antarctic Treaty Consultative Meeting, aimed at minimizing the impact of such activities. Discharge from vessels is regulated under the Protocol and instruments of the International Maritime Organization.

28.2.6. Governance in the Polar Regions

Dealing with the stresses of climate change and other changing factors in the Polar Regions requires robust governance regimes. The Arctic and Antarctic Regions are governed by quite different regimes that reflect their geographic and political contexts. The Arctic is essentially an ice-covered ocean surrounded by sovereign states whereas the Antarctic is a continental landmass, surrounded by ocean, that has remained unpopulated except for isolated research stations.

The Antarctic is governed by a number of conventions, collectively called the Antarctic Treaty system. The number of States parties to the Treaty has grown from the original 12 nations that were involved in the Antarctic during the International Geophysical Year of 1957-58, to 50 parties today. The Treaty, negotiated during the Cold War tensions, was signed in December 1959 and entered into force on June 1961. The primary purpose of the Antarctic Treaty is to ensure "in the interests of all mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord" and "freedom of scientific investigation in Antarctica." The Treaty effectively holds in abeyance all claims to territorial sovereignty in Antarctica. It is generally seen as one of the "success stories" of contemporary international law (Rothwell, 2012). The Protocol on Environmental Protection to the Antarctic Treaty was signed in 1991 and entered into force in 1998. Its objective is the comprehensive protection of the Antarctic environment and dependent and associated ecosystems. The Protocol designates Antarctic Treaty area as a "natural reserve devoted to peace and science", prohibits any activity relating to mineral resources other than scientific research, requires the prior environmental impact assessment of proposed activities, and establishes a range of other environmental standards and requirements. The other active component of the Antarctic Treaty System is the Convention for the Conservation of Antarctic Marine Living Resources, which applies to all marine areas south of the Antarctic Convergence overlapping in jurisdiction with the Antarctic Treaty. Both of these conventions provide mechanisms for managing the effects of climate change in their areas of jurisdiction.

The parallel for the Arctic is the Arctic Council which was formally established in 1996 as a high level intergovernmental forum to provide a means for promoting cooperation, coordination and interaction among the eight Arctic States and the Arctic Indigenous peoples' organizations on common issues such as sustainable development and environmental protection. The Arctic Council is supported by several Working Groups. The International Arctic Science Committee (IASC) which preceded the Arctic Council, being established in 1990, like SCAR is also under the umbrella of the International Council of Science (ICSU). The Arctic Council and the IASC carried out the Arctic Climate Impacts Assessment (ACIA, 2004). The most recent activity of the Arctic Council, in conjunction with IASC, was the Snow, Water, Ice and Permafrost Assessment (SWIPA, 2012). An Aeronautical and Maritime Search and Rescue agreement, signed in 2011, is the first legally-binding agreement negotiated under the auspices of the Arctic Council. Despite such achievements, the Arctic Council is still regarded by some as tentative – a "soft law regime" (Rothwell, 2012).

Since climate change, particularly in the Arctic, has been observed to be occurring faster than the global trend, it is not surprising that it has been a priority subject for the international organisations established under the Antarctic Treaty system and the Arctic Council (Rayfuse, 2007; Byers, 2010). In 2010 the Antarctic Treaty parties convened an Antarctic Treaty Meeting of Experts (ATME) on Climate Change Implications for Antarctic Management and Governance, which examined the ACCE report (Turner *et al*., 2009) and identified 30 recommendations for consideration by the Antarctic Treaty Consultative Meeting (ATCM). The majority of the recommendations related to actions that could be taken by the Parties in Antarctica and within the scope of the Antarctic Treaty system, but several recognised the importance of conveying information about Antarctic climate change to international bodies discussing and climate change. Accordingly, the Parties have begun to contemplate the scope of their role in addressing the implications of climate change for management of the Antarctic Treaty area, possibly including opportunities for enhanced engagement with international organisations discussing climate change action.

Retreating sea-ice in the Arctic is expected to open up new commercial opportunities for gas, petroleum and mineral activities (Borgerson, 2008; Paskal, 2010); UNDP, 2009). The establishment of Exclusive Economic Zones has proceeded in peaceful fashion and the provisions of the United Nations Convention on the Law of the Sea (UNCLOS) and the UN Commission on the Limits of the Continental Shelf have generally been respected (Gleditsch, 2011). Such regimes can be expected to be important in addressing any competition between the Arctic coastal states for control over outer continental shelf claims. Retreating ice will also open up new opportunities for shipping as well for a more intensive use of the Northern Sea Route and North-West Passage (Konyshev V.N., 2011). This may increase competition for the control of these passages and, at the same time, emphasize the need for effective pollution prevention regulations such as the Government of Canada's Arctic waters Pollution Prevention Act of 1970 (Pharand, 1988). Some scholars have argued that there could be sovereignty-related disputes in support of broad economic interests (Konyshev V.N., 2011) although most observers seem to agree with Haftendorn (2010) that this is not expected, nor is a military conflict among the contenders (Gleditsch, 2011).

These issues and others illustrate the importance of science-based innovation in the conservation, management and governance of Arctic resources.

28.2.6.1. Indigenous Peoples, Climate Change, and Traditional Knowledge

Arctic indigenous peoples – the original Native inhabitants of the region – are estimated to number between 400,000 and 1.3 million. (Bogoyavlensky and Siggner, 2004; Galloway McLean, 2010). The percentages of the populations of indigenous peoples in the Arctic range from 3-4 % in Russia to 80% in Greenland. (Galloway McLean, 2010) Indigenous populations in the Arctic are considered especially vulnerable to climate change, due to their close relationship with the environment and its natural resources for physical, social, and cultural well-being (Nuttall *et al*., 2005; Parkinson, 2009). Arctic residents in general depend heavily on the region's terrestrial, marine and freshwater renewable resources, including fish, mammals, birds, and plants; however, the ability of indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by the unprecedented rate of climate change. (Nakashima *et al*., 2011) The risks are spatially and temporally heterogeneous and encompass potential synergies with other, non-climatic drivers, such as general globalization and

resource development (e.g., oil and gas extraction, mining) (Vuojala-Magga *et al*., 2011), and the prevalence in many indigenous communities of poverty, marginalization, and resulting health disparities. (Abryutina, 2009).

Indigenous and local communities as well as scientists are therefore forced to think in terms of multiple stressors, since in any one area there may be significant synergies resulting from combinations of rapid climate and/or land use change coupled, in the worst cases, with non-adaptive forms of governance. (Sydneysmith *et al*., 2010; Kumpula *et al*., 2011). In habitats across the Arctic, climate changes are affecting these livelihoods through decreased sea ice thickness and extent, less predictable weather, severe storms, changing seasonal melt/freeze-up of rivers and lakes, changes in snow type and timing, increasing shrub growth, permafrost thaw, and storm-related erosion which, in turn, are causing such severe loss of land in some regions that a number of Alaskan villages are having to relocate entire communities (Mahoney *et al*., 2009; Forbes and Stammler, 2009; Bartsch *et al*., 2010; Weatherhead *et al*., 2010; Brubaker *et al*., 2011b; Bongo *et al*., 2012; Eira *et al*., 2012; McNeeley, 2012; Huntington and Watson, 2012)Bronen, 2011)

The historical, accumulated knowledge of indigenous peoples (also known as indigenous, traditional, or local knowledge which also includes "traditional ecological knowledge" or TEK) is increasingly emerging as a critical source of information for comprehensively addressing the impacts of environmental and other changes as well as the development of appropriate adaptation and response strategies for indigenous communities. (Nakashima et al 2012;Vuojala-Magga *et al*., 2011) Reflecting the importance of the incorporation of this knowledge for adaptation and response strategies, the IPCC Fourth Assessment Report acknowledged indigenous knowledge as "an invaluable basis for developing adaptation and natural resource management strategies in response to environmental and other forms of change" and this IPCC Fifth Assessment includes a number of sections on indigenous knowledge in several chapters. (e.g., Polar Regions, 28.2 – 28.4 and Human Security, 12, 12.3.2) Indigenous Knowledge has also been recognized at the global level in a recent report prepared by UNESCO for the IPCC AR5, which pays special attention to the systematic observations provided by Arctic indigenous communities (Nakashima *et al*., 2011)

Indigenous knowledge has been characterized as "knowledge and know-how accumulated across generations, and renewed by each new generation, which guide human societies in their innumerable interactions with their surrounding environment" (Nakashima et al 2012) and can be considered traditional due to its origins in traditional cultures.(Vuojala-Magga *et al*., 2011) Indigenous knowledge and TEK consist of beliefs, rituals, and understandings about the dynamic relationships between living entities and the environment, and is a body of knowledge that has evolved through adaptive processes and handed down through generations (Berkes, 2008; Reinert *et al*., 2009; Nakashima *et al*., 2011) Indigenous knowledge and TEK are useful for detecting and adapting to climate change impacts because climate models often have low resolution at local and even regional scales, and this is precisely the scale at which indigenous observations emerge. Examples include Sámi reindeer herders' knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter and spring reindeer rangelands (Roturier and Roué, 2009; Riseth *et al*., 2011; Eira *et al*., 2012). While indigenous knowledge is important for climate assessments (Huntington *et al*., 2004; Salick and Ross, 2009; Green and Raygorodetsky, 2010) Ford et al., 2011), not all indigenous community members share the same expert and indigenous knowledge; hence, they face the need to conceptualize their adaptation strategies within their own social, political, and cultural contexts (Ford *et al*., 2011).

In many cases, indigenous knowledge, traditional ecological knowledge, and Western science detect the same climate change impacts, thereby increasing confidence about the effects of climate change on Arctic environments and societies. In some instances, however, the interpretations differ and caution is recommended before drawing firm conclusions (Huntington *et al*., 2004). The perception of change at the community level can be as important as scientifically detectable or measurable change in determining whether and how to respond to indirect environmental or more direct anthropogenic drivers (Alessa et al. 2008). Indigenous knowledge and TEK have long been incorporated into co-management regimes in the North American Arctic (Forbes and Stammler, 2009). Its application to date in Eurasian renewable resource management institutions has been mostly limited to marine fisheries (Jentoft 2000). In both North America and northernmost Europe, the results to date are mixed and there is ample room for improvement (Berkes and Dyanna, 2001; Kofinas, 2005; Ulvevadet, 2008; Meek *et al*., 2008; Berkes, 2009; Dowsley 2009).

At a more basic level, indigenous knowledge and TEK have proven applications in broadening our understanding of ongoing climate and land use changes and their combined ecological and social implications across the circumpolar North (Sydneysmith *et al.*, 2010; Riseth *et al.*, 2011; Kumpula *et al.*, 2012). At Clyde River, Nunavut, Canada, Inuit experts and scientists note that wind speed has increased in recent years and that wind direction changes more often over shorter periods (within a day) than it did during the past few decades (Gearheard *et al.*, 2010). In Norway, Sámi reindeer herders and scientists are both observing direct and indirect impacts to reindeer husbandry such as changes in snow and ice cover, forage availability and timing of river freeze-thaw patterns from increasing temperatures. (Maynard and Conway, 2008; Eira *et al.*, 2012). On the Yamal Peninsula in West Siberia, detailed Nenets observations and recollections of iced over autumn and winter pastures due to rain-on-snow events have proven suitable for calibrating the satellite-based microwave sensor SeaWinds (Bartsch *et al.*, 2010) and NASA's AMSR-e sensor (Bongo *et al.*, 2012).

In the Canadian Arctic, there is agreement between Inuit knowledge and scientific studies about the thinning of multiyear sea ice; the shortening of the sea ice season; the declining extent of sea ice cover, with Inuit experts reporting less predictability in the sea ice and more hazardous travel and hunting at ice edges; a decrease in the quantity of multiyear and first-year sea ice; an increasing distance of multiyear ice from the shore; and variability and uncertainty in sea ice during transition months of the year, when freeze-up and breakup occur. (Ford et. al., 2009; Aporta *et al.*, 2011).

While Arctic indigenous peoples are facing unprecedented impacts to their life ways from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they have already implemented some creative ways of adapting (Cruikshank, 2001; Forbes, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Cullen-Unsworth *et al.*, 2011; Alexander *et al.*, 2011; Bongo *et al.*, 2012)). For example, they are combining indigenous knowledge with western scientific knowledge about the ecology and its interrelationships with economic and cultural systems to develop the resilience of ecological and social systems and to identify those factors which can enhance that system's potential for self-sufficiency and sustainable development (Forbes, 2006; Maynard *et al.*, 2010; Gearheard *et al.*, 2011). Examples of indigenous adaptation strategies have included changing resource bases, shifting land use and/or settlement areas, combining technologies with Indigenous knowledge, changing timing and location of hunting, gathering, herding, and fishing areas, and improving communications and education (Galloway McLean, 2010; Bongo *et al.*, 2012). Local and state governance regimes or other institutions too rigid to accommodate relevant Indigenous knowledge or local knowledge are likely to increase vulnerability to rapid change, whereas, flexible institutions responsive to indigenous and local knowledge in real time can enhance resilience (Meek *et al.*, 2008; Sydneysmith *et al.*, 2010; Kumpula *et al.*, 2012)

28.2.6.2. Reindeer, Climate Change, Development, and Adaptation

Reindeer husbandry has had a long important history in the Arctic, especially for the many indigenous people in Norway, Sweden, Finland, Russia, Mongolia, China, US, Canada, and Greenland. (Magga et al, 2011) Reindeer husbandry as a livelihood now involves about 100,000 herders and approximately 2.5 million semi-domesticated reindeer. (Oskal, 2008) Interactions between reindeer (*Rangifer tarandus* L.) and humans date from the late Pleistocene onward and wild and semi-domestic animals continue to be essential to indigenous peoples throughout the Arctic for a diversity of purposes. (Oskal, 2008; Forbes and Kumpula, 2009) Contemporary reindeer management functions as a coupled social-ecological system characterized by a nomadic or semi-nomadic lifestyle undertaken by family- or shift-based, indigenous and mixed ethnicity communities (Vuojala-Magga *et al.*, 2011;Forbes, 2006). Migration routes within and among seasonal pastures vary widely from tens to several hundred kilometres. The reindeer lies at the very core of these communities, providing primary food, economic base, way of life, clothing, mythologies, and worldviews, but is facing increasing challenges from unprecedented changes in their climate and weather as well as accelerating changes in land use, (Stammler, 2005; Forbes, 2006; Oskal, 2008; Paine, 2009; Vuojala-Magga *et al.*, 2011),

Such changes in the climate are already affecting the reindeer herding communities through greater variability in temperature, and precipitation. This increased variability affects overall weather patterns and exerts strong influence on snow quality, quantity and duration (Bulygina *et. al.*, 2009; Bulygina *et. al.*, 2010; Callaghan *et al.*, 2011b) –

very critical environmental variables for reindeer sustainability (Eira *et al*., 2012). Reindeer must forage continually and any significant impediment to their ability to access forage under the snow cover each day during winter can threaten their survival (Vuojala-Magga *et al*., 2011). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow which then block the animals' access to their forage and subsequent starvation. (Bartsch *et al*., 2010; Bongo *et al*., 2012; Eira *et al*., 2012) Annual migration patterns between summer and winter pastures are being challenged due to changes in the freeze-thaw cycles of rivers and lakes, with spring thaws occurring earlier and soft ice no longer able to support the reindeer as they try to cross and by the appearance of new infrastructure such as oil and gas pipelines, roads, and buildings (Vuojala-Magga *et al*., 2011). Warmer Arctic temperatures have increased insect harassment causing major interference with foraging (Kitti *et al*., 2006). Other climate change impacts are also occurring, which have similarly important implications for reindeer pasture availability and migration routes. (Maynard et al, 2010) With the lack of land-fast ice along the Arctic coasts in recent years, longer summers, and intense pressure to develop oil, gas and minerals in the North, the Arctic regions are becoming far more accessible to humans and industrial development, resulting in additional sources of increasing and irreversible loss of pasturelands (Kitti *et al*., 2006; Forbes and Stammler, 2009; Bongo *et al*., 2012).

Over the millennia, wild and semi-domestic reindeer populations have developed a strong resiliency to climate change and variability because, in fact, it is a species which has constantly been subjected to extensive weather-related variations on a day-to-day basis as well as during seasonal migrations. (Klein *et al*., 2005; Turi, 2008). However, in recent years, these successful adaptation strategies which have guided their survival have been challenged by unprecedented rates of climate change and additional external factors such as changing government policies, sharply increasing oil and gas development and mining activities, overall pasture loss, and blocking of migration routes. (Forbes, 2006; Bongo *et al*., 2012). In fact, the increasing global demand for energy and mineral resources plus an aggressive development of oil and gas fields as well as mining of other resources are encouraging rapid development with its associated infrastructure, pipelines, drill pads, roads, and pollution all across the once-rich pasture lands of the reindeer seasonal migration routes (Forbes and Stammler, 2009; Kumpula *et al*., 2012). In many locations, the associated infrastructure is being built across migration routes in Northern Russia, often blocking pathways to seasonal pastures and eliminating camping and fishing site for herders (Rees *et al*., 2008; Kumpula *et al*., 2011; Kumpula *et al*., 2012; Degteva et al, 2010). This is especially important as it is well-known that female reindeer and their calves will avoid humans and their activities as well as physical infrastructure (Vuojala-Magga *et al*., 2011).

Of particular concern today, it is estimated that the Arctic may contain approximately 25 % of the world's remaining undeveloped petroleum resources and climate warming is accelerating access to northern lands for development. (Forbes, 2009). For example, Yamal in Western Siberia has approximately 90 % of Russia's gas reserves, but at the same time represents the largest area of reindeer herding in the world (Jernsletten and Klokov, 2002; Stammler, 2005; Forbes and Kumpula, 2009). Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to the loss of "available room for adaptation" for reindeer husbandry (Forbes et al. 2009; Nuttal et al, 2005). Furthermore, it is anticipated that there will be sharp increases in future oil and gas and other resource development in the Russian North and other Arctic regions – along with its associated infrastructure, pollution, and other by products of development – which will, in turn, reduce the availability of available pasturelands for the reindeer and the indigenous communities associated with them. (Derome and Lukina, 2010). Together with the symptoms of ongoing climate warming cited above, the combination of these factors presents major concerns for the future of reindeer husbandry, the well-being of the Arctic indigenous and other communities, especially the reindeer herding communities, and the ability to adapt to future changes (Forbes *et al*., 2009; Kumpula *et al*., 2011; Vuojala-Magga *et al*., 2011; Kumpula *et al*., 2012).

28.3. Key Projected Impacts and Vulnerabilities under Different Climate Pathways

28.3.1. Hydrology and Freshwater Ecosystems

28.3.1.1. Arctic

Accompanying projected increases in Arctic river flow (see WGII Chapter 3) is a shift to earlier timing of spring runoff (Dankers and Middelkoop, 2008; Pohl *et al.*, 2009; Hay and McCabe, 2010) and an increase in the magnitude of spring snowmelt, particularly in areas with winter temperatures <-30ºC (Adam *et al.*, 2009). Based on the results of a study on the Canadian Archipelago (Lewis and Lamoureux, 2010), spring fluxes of sediment are also projected to increase with spring flows (+100 to 600% by the end of the 21st century based on CGCM3 A1b and A2 scenarios, respectively). Such estimates are considered conservative, however, because the modelling did not consider the potential for enhanced permafrost thaw.

Projected increases in permafrost thaw (see WGI Chapter 4) will also continue to affect the dynamics of thermokarst lakes (e.g., appearance of new lakes and drainage of some existing ones) and related ecological effects as outlined in Section 28.2.1.1. Similarly, the loss of glacier ice masses will alter spatial and temporal dynamics in runoff accompanied by changes to sediment loads, water chemistry and thermal regimes, and related channel stability, habitat and biodiversity (Milner *et al.*, 2009; Moore *et al.*, 2009).

Although snow, freshwater ice and permafrost affect the morphology of arctic alluvial channels, their future combined effects remain unclear (McNamara and Kane, 2009). In the case of small permafrost streams, however, even if the thickness of their hyporheic zones does not substantially deepen, longer projected periods of flowing water will modify nutrient and organic matter processing in this important biological stratum (Greenwald *et al.*, 2008; Zarnetske *et al.*, 2008). In terms of broader aquatic productivity, long-term negative impacts of increased sediment load could outweigh any positive effects associated with increased nutrient loading (Bowden *et al.*, 2008).

Thawing permafrost and changes in the hydrological regime of the Arctic rivers, particularly those traversing regions affected by industrial developments, will increase the contaminant flow (Nikanorov *et al.*, 2007). Studies in the Lena and Kolyma rivers indicated that water pollution by oil is one of the key factors currently affecting the pelagic ecosystems in the coastal zone, which is likely to increase under warmer climatic conditions (Nikanorov *et al.*, 2007; Nikanorov *et al.*, 2011a; Nikanorov *et al.*, 2011b)

Changes to the dynamics of spring freshet on large Arctic rivers is also projected to change from a reduction in their south to north thermal gradients and, hence, severity of river-ice breakup and ice- jam flooding (Prowse et al., 2010). Such a conclusion is based on GCM-ensemble projections of air temperatures (SRES A2 scenario; 2041–2070 & 2071–2100) along the 4 largest arctic rivers, Lena, Ob, Yenisei and Mackenzie compared to current (1979–2008) conditions. One caveat made on such a projection is the, as yet to be fully evaluated, complicating effect on break-up dynamics of the above noted increases in the magnitude of spring snowmelt.

A reduction in ice-jam flooding would have positive benefits for river-side northern communities and infrastructure but it could also alter the ecology of delta-riparian (Lesack and Marsh, 2010) and coastal-marine (Emmerton *et al.*, 2008) ecosystems. The quality of river water entering the marine environment during the spring period is also projected to be affected with the reduction or loss of stamukhi lakes and their distinct microbial assemblages, which play a key functional role in processing river inputs to the marine ecosystems (Dumas *et al.*, 2006; Galand *et al.*, 2008).

Future changes to lake-ice regimes are also projected to affect lentic ecology. Based on a modelling study of hypothetical 20-m deep lakes in the Northern Hemisphere (between 40° and 75°N), projections from a one-dimensional lake model driven by output from the CGCM3 indicate that future (SRES A2 scenario; 2040–2079 compared to 1960–1999) lake conditions will be characterized by an overall increase in lake-water temperature, and earlier and longer-lasting summer stratification (Dibike *et al.*, 2011). Other projections include: freeze-up delayed 5-20 days, break-up advanced by 10-30 days, thickness decreased 10-50 cm, and cover composition modified by changes in snow loads with white ice changing by -20 to +5 cm – the higher latitudes being an area most increase

because of the combination of increases in winter snowfall and thinner ice cover that would promote enhanced white-ice formation.

The loss or reduction in duration of ice cover on lakes and corresponding changes in their thermal regimes can affect a number of aquatic processes (Prowse and Brown, 2010a). Paleolimnological research has shown for a site in the Siberian Arctic that periods of highest primary productivity were associated with warm, ice-free summer conditions, while the lowest rates were coincident with periods of perennial ice (Melles *et al.*, 2007). The projected changes in snow and white ice coverage can also affect levels of secondary productivity, such as in fish e.g., (Borgstrøm and Museth, 2005; Prowse *et al.*, 2007). Patterns of species richness and diversity are also projected to change with alterations to ice and open-water durations, with increased open water periods favouring the development of new trophic levels and colonization of new aquatic species assemblages (Vincent *et al.*, 2009). For some lakes, however, the loss of ice will result in the loss of suitable habitat, both in availability and quality (Vincent *et al.*, 2008). For example, lake-ice duration has a controlling influence on the levels and mixing of dissolved oxygen (e.g. (Laurion *et al.*, 2010). The above-noted projected shifts to increased summer stratification will increase the possibility of oxygen depletion and even anoxia in the bottom waters and reduce the habitat availability for high oxygen-demanding biota during such periods. By contrast, with greater atmosphere-water gas exchange resulting from longer open-water periods, the occurrence of winter kills of resident fish are expected to be reduced and produce cascading effects on lower trophic levels (Balayla *et al.*, 2010).

In addition to habitat alterations, geochemical responses of Arctic lakes will be altered. As observed for certain Arctic thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production (Metje and Frenzel, 2007; Laurion *et al.*, 2010). Because temperature sensitivity has a stronger control over methane production than oxidation (Duc *et al.*, 2010), elevated water temperatures will enhance methanogenesis, causing increased methane release from sediments. The net balance of these two processes operating under a broad range of future changing environmental factors, however, remains to be quantified (Walter *et al.*, 2007; Walter *et al.*, 2008; Laurion *et al.*, 2010).

As well as methane, increased water temperatures are projected to lead to reduced organic carbon (OC) burial. Projections, based on a range of six climate warming scenarios (IPCC, 2007), indicates that there will be a 4-27% decrease (0.9-6.4 TgC yr-1) in OC burial in lake sediments across the entire northern boreal zone by the end of the 21st Century as compared to rates for the approximately last half-century (Gudasz *et al.*, 2010). Although these estimates are based on an assumption that future organic carbon delivery will be similar to present-day conditions, even with enhanced delivery as to be generated by thawing permafrost, higher water temperatures will increase organic carbon mineralization and thereby lower burial efficiency. The amount of burial will also depend on lake depth and mixing regimes. In the case of warming shallow lakes that are not thermally stratified, there will be a greater opportunity for water-sediment mixing and hence, greater carbon recycling back into the water column. Alternatively, in lakes that become increasingly thermally stratified lakes, carbon sinking below the thermocline tends not to return to surface waters until the fall turnover, thereby decreasing the probability of sediment-stored carbon being returned to the water column (Flanagan *et al.*, 2006).

Changes in ice cover, thermal regimes and stratification patterns will also affect the fate of contaminants in northern lakes. Higher water temperatures can enhance, for example, the methylation of mercury and modify food-web and energy pathways, such as through enhanced algal scavenging (a major foodweb entry pathway for mercury) resulting in increased mercury bio-availability to higher trophic levels (e.g., predatory fish) (Outridge *et al.*, 2007; Carrie *et al.*, 2010;AMAP, 2011).

28.3.1.2. Antarctic

Previous assessments have been reinforced in this assessment. The most vulnerable region for change in Antarctic freshwater systems are the northern Antarctic Peninsula and maritime Antarctic islands in the southern Scotia Arc, which are within a few degrees of the melting point, so a small shift in temperature regimes can have widespread ecosystem impacts. These range from catastrophic and immediate impacts such as loss of bounding ice masses causing drainage of freshwater and epishelf lakes (Smith *et al.*, 2006; Hodgson, 2011), to more gradual impacts

associated with changes in the amount and duration of catchment ice and snow cover, accelerated glacier melting, and declining volumes of precipitation falling as snow.

As in Arctic lakes, the most marked changes are expected to be associated with changes in the thickness and duration of seasonal ice cover, longer melt seasons and larger volumes of water flowing into the lakes (Lyons *et al.*, 2006). A longer ice free season may cause changes in a lakes mixing regime and release of solutes from the sediments, increased light (including ultraviolet), higher water temperatures, increased CO_2 exchange and conditions more favorable for the growth of the plankton, periphyton and benthic communities (Hodgson and Smol 2008). However in some systems the very high light irradiances experienced during the summer can substantially inhibit algal blooms under ice free conditions (Tanabe *et al.*, 2007). In shallow lakes this favors the growth of benthic cyanobacteria species that can synthesise a number of light screening compounds (Hodgson *et al.*, 2005). In other lakes, increases in meltwater supply may reduce light penetration due to an increase in suspended solids, and it remains uncertain whether this will offset the increases in the underwater light regime predicted as a result of extended ice free periods (Quesada *et al.*, 2006).

Under a warming climate an increase in catchment microbial biomass is likely because of the increased water supply from glacial melt and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved organic carbon delivery to lakes. This organic supply will promote growth and reproduction in the benthos and plankton. Another observation is that where more melt water is available, input of freshwater into the mixolimna of deeper lakes can increase stability and this, associated with increased primary production, will lead to higher organic carbon flux. Such a change will have follow–on effects including potential anoxia, shifts in overall biogeochemical cycles and alterations in the biological structure and diversity of ecosystems (Lyons, Laybourn-Parry et al. 2006). Conversely, in shallow lakes where water is heated above the 3.98°C maximum density only very moderate winds will be required to cause wind–induced mixing through the ice free periods influencing plankton communities, gas exchange and biogeochemical processes.

Away from glacial forelands, future regional patterns of water availability are unclear, but increasing aridity is likely in some areas of the continent in the long-term (Hodgson *et al.*, 2006b) and on subantarctic islands (Smith Jr *et al.*, 2012). Lakes can dry up completely causing local extinctions or retreat into cryptic or resistant life-cycle stages, as experienced in Arctic lakes (Smol and Douglas, 2007b).

Studies have also shown that once cold freshwater habitats in Antarctica can be colonised by biota from northern refuges in maritime and sub-Antarctic areas (Barnes *et al.*, 2006). There is *medium confidence* that future elevated temperatures will allow the sub- and maritime Antarctic taxa to re-invade and establish self-maintaining populations on the Antarctic continent (Hodgson *et al.*, 2006b).

For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman *et al.*, 2010) whichhave evolved on the continent over multiple glacial interglacial cycles (Vyverman *et al.*, 2007; Vyverman *et al.*, 2010; Fernandez-Carazo *et al.*, 2011) and allows for the possibility that Antarctic lakes may contain species that are relicts of Gondwana (cf. (Convey and Stevens 2007)). These species cannot be replaced from lower latitudes if they were to experience continental extinction as a result of climate changes.

As in previous assessments, expanding fur seal populations in some breeding areas will increase nutrient enrichment of the freshwater habitats. As well, alien species may be more easily introduced into these environments through human activities and poses a greater threat than colonisation across the natural barriers of the Southern Ocean. increase, even though no reports of alien freshwater species have been reported to date (Frenot *et al.*, 2005).

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Arctic

Arctic marine ecosystems are complex and thus predicting their future under climate change is challenging. In the Bering Sea and Barents Seas, there is *high confidence* based on a long history of observed responses of species to interannual and decadal variability in climate that climate change will impact marine ecosystems. While there is abundant evidence that climate induced shifts in ocean conditions impact marine ecosystems, predictions of the magnitude and spatial extent of ecosystem change are uncertain. Regions at lower latitudes have a rich basis of scientific literature and long time series from which to provide the foundation for scientific conclusions. Farther north, the cost and infrastructure needed to conduct research in the region results in fewer researchers working in the area and fewer empirical observations for drawing statistical inference and conclusions.

In the Arctic Ocean, a coupled bio-physical model was used to simulate changes in lower trophic levels under changing climate conditions for the period 1988 – 2007 (Zhang *et al.*, 2010). This model projected increased marine primary productivity consistent with satellite observations.

There is *medium confidence* that in the deep basins of the Arctic Ocean changes in stratification and the number of ice free days will lead to a greater drawdown of nutrients and higher pelagic primary production. It is unclear whether the large-bodied copepods (*Calanus* spp.) may have the capacity to graze this down phytoplankton levels in summer (Olli *et al.*, 2007).

28.3.2.1.1. Projected impacts on phenology
(timing of spawning, timing of settlement, duration of growing season, age at maturity)

Historical records show Atlantic cod can adapt to local conditions by shifting key vital rates (diet, growth rate, maturity schedule and survival rate) and reproductive periods to accommodate differences in regional prey availability, predator avoidance and environmental conditions (Ormseth, 2007; Sundby and Nakken, 2008;Vikebo et al., 2007). Efforts to project how these physiological and behavioral responses will impact marine ecosystems are the focus of a large interdisciplinary ecosystem modeling effort in the Bering Sea (Wiese *et al.*, 2012).

28.3.2.1.2. Projected spatial shifts in response to climate

In the northern Bering Sea, reduced sea-ice and warmer temperatures in the late 1990s and early 2000s led to a northward movement of benthic feeders (e.g. walrus, grey whales). This is thought to have been related to a reduced flux of particulate organic material to the benthos, because of increased pelagic grazing (Grebmeier *et al.*, 2006). Further climate warming may lead to an extension of these conditions farther north (e.g. into the Chukchi Sea). If this occurred this would provide higher levels of prey for pelagic planktivores and baleen whales, but could have a negative impact on the benthic planktivores. In addition, some planktonic predators may suffer if the large lipid-rich Arctic Calanus species (*C. glacialis, C. hyperboreus*) are displaced by the smaller boreal forms (*C. finmarchicus, C. marshallae*) (Karnovsky *et al.*, 2010).

Modeling studies project that climate change will shift the bio-climate envelopes of marine fish stocks resulting in an increase in biodiversity in the Arctic (Cheung *et al.*, 2009). Qualitative data synthesis and modeling shows that the response of fish stocks to changes in bio-climatic envelopes may be more complicated.

There is *medium confidence* that the waters off the coasts of Europe will provide the potential for increased production because of the combined effects of intrusion of Atlantic water over the relatively broader shelf regions and advective corridors for larval drift and range expansion of spawners. In the Barents Sea, Huse and Ellingsen (2008) used a spatially explicit coupled bio-physical model forced with future climate scenarios to project the implications of climate change on the spawning distribution of capelin in the Barents Sea. Projections show that the

spawning distribution of capelin will shift to the east and new spawning grounds will be colonized. A key factor governing this expansion will be the availability of pelagic prey.

In the Bering Sea, there is *medium confidence* based on observations that planktivorous species like walleye pollock in the eastern Bering Sea will shift their distribution in response to shifts in ocean temperature (Kotwicki *et al*. In Press). However, in the northern Bering Sea the persistence of cold winter conditions in the Arctic coupled with the life history factors will restrict or retard the movement of several sub-arctic fish and shellfish species into the Arctic (Sigler *et al*., 2011; Stabeno *et al*., 2012; Hunt Jr. *et al*., 2013; Hollowed *et al*., In Press). There is *medium confidence* based on qualitative data synthesis that fewer commercial fish species from the Pacific are expected to colonize the Arctic because of the shallow depth of the Bering Strait, the continued formation of the cold pool in the northern Bering Sea, and the comparatively weaker flow into the Arctic.

28.3.2.1.3. Projected impacts on fish and shellfish production in response to climate

In the Bering Sea there is *medium confidence* based on observations, that increased summer sea surface temperatures will cause a decrease in the abundance of energy rich zooplankton in the eastern Bering Sea. Decreased availability of energy rich zooplankton is expected to result in lower survival of walleye pollock stocks in the eastern Bering Sea (Hunt *et al*., 2011). Mueter et al. (2011) incorporated this relationship between ocean zooplankton into a single species stock projection model to assess the implications of future climate scenarios on the future production of Bering Sea walleye pollock. Results showed that walleye pollock stocks were projected to decline by 2050 due to reduced survival in the first year of life although there is considerable uncertainty in the projections. Efforts to extend these models for use in projecting annual production in the Arctic are under development.

28.3.2.1.4. Cumulative effects

The cumulative effects of climate change on the phenology, spatial distribution and production of fish and shellfish are uncertain and the projected outcomes will differ by species and region. While changes in the distribution and abundance of fish and shellfish have been observed in the Arctic and its surrounding seas, the absence of a historical baseline in the Arctic Ocean inhibits attribution of observed changes in that region to climate change.

28.3.2.2. Antarctica and the Southern Ocean

Continued increasing temperatures in the Southern Ocean are likely to result in increased metabolic costs in many pelagic species and movement south of the northern distribution of polar species and southern distribution of temperature and subantarctic species. Movement of the frontal systems and associated oceanographic mesoscale features such as eddies and filaments where increased productivity attracts top predators may not only cause a shift southward of many pelagic taxa but also make it energetically inefficient for some land-based predators to pursue those prey from their more northerly subantarctic breeding sites (Péron *et al*., 2012; Weimerskirch *et al*., 2012).

For Antarctic krill, the prognosis overall is ambigous. Krill will naturally respond to warming with an increased metabolic rate but its overall growth rate is dependent on having enough food to support it. The changes in temperature at the Antarctic Peninsula will enhance the productivity of krill but the response is likely to be negative at South Georgia because of the already warmer temperatures in that area (Wiedenmann *et al*., 2008). Models of recruitment and population dynamics indicate that the biomass of krill will decline if surface warming continues, but preliminary projections are highly uncertain (Murphy *et al*., 2012b). Recruitment success of krill may also decline in the long term as a result of impacts of ocean acidification on larval development (Kawaguchi *et al*., 2011). Overall, regional variation of factors that could impact directly on krill both positively and negatively will likely result in region-specific responses and depend on the ability of krill to adapt physiologically and behaviourally. Recently, it has been shown that krill can exploit the full depth of the ocean, thus their potential habitat is far greater than once thought and might provide avenues to escape further warming (Schmidt *et al*., 2011) but may make them less accessible to predators (Constable *et al*., submitted). These factors could lead to the marine food webs around the

South Atlantic islands with their current krill-based systems becoming more like the fish-based ecosystems of the Indian Ocean sector (Trathan *et al.*, 2012; Murphy *et al.*, 2012a; Murphy *et al.*, 2012b).

Projections show that the loss of summer sea ice from the west Antarctic Peninsula are expected to result in ice-dependent seals declining in WAP and being replaced by southern elephant seals and/or other seal species that are not dependent on sea ice (Costa *et al.*, 2010). Importantly, the change in duration of the winter sea ice season and a possible continued change in timing of the season could impact on the potential productivity of phytoplankton because of the mismatch in timing of optimal growing conditions at the time of sea ice melt and the available light (Trathan and Agnew, 2010). This mismatch in timing can also propagate through the food web to impact on krill and upper trophic levels that depend upon krill.

Coastal environments will be impacted by the dynamics of fast ice, ice shelf and glacier tongues. These factors will positively affect local primary production and food web dynamics (Peck *et al.*, 2009) but negatively affect benthic communities (Barnes and Souster, 2011). Projections of the response of Emperor penguins and Southern Ocean seabirds based on AR4 model outputs for sea ice and temperature indicates that general declines in these populations are to be expected if sea ice habitats decline in the future (Barbraud *et al.*, 2011; Jenouvrier *et al.*, 2012) but these responses are also expected to be regionally specific because of the regionally different expectations of change in the ice habitats.

28.3.3. Terrestrial Environment and Related Ecosystems

28.3.3.1. Arctic

Projections of future ecosystem distribution and production are based on one of two approaches: field experiments that simulate future environments such as increases in summer air temperature, soil temperature, precipitation, UV-B radiation, atmospheric CO2 concentrations, soil nutrients, snow depth, snow cover duration and or facilitation/competition from pre-existing species, and mathematical models. Both approaches have uncertainties. However, both approaches concur that climate warming will result in a generally northward migration of vegetation zones dominated by the particular responsiveness of woody plants – both shrubs and trees.

Model projections include equilibrium models based on climate and vegetation zone distributions and also dynamic vegetation models based on physiological and ecological processes.

Many models project a general northward movement of the boreal forest under a warming climate, that will displace between 11% and 50% of the tundra within 100 years (Callaghan *et al.*, 2005; Wolf *et al.*, 2008; Vygodskaya et al., 2007; Sitch et al., 2008; Tchebakova et al., 2009) in a pattern similar to that which occurred during the early Holocene climatic warming

The BIOME 3 equilibrium model applied to Europe and northern Asia projected general displacement of tundra by forest that amounted to between 10 and 35% (the minimum in Scandinavia and the maximum in central-Northern Siberia) (Harding et al. (2001). Estimates of displacement of tundra by forest from similar models varied up to a maximum of 50% (ACIA 2005). A recent model for Russia projected that as early as the first quarter of the 21st Century, changes will occur in the boreal zones of the European part of Russia and the Western region (Anisimov et al., 2011). By 2060, tundra vegetation will be displaced from the mainland and from further towards the East where it will remain only in the Far East and Primorye.

Dynamic vegetation models applied to Europe and the Barents Region project a general increase in net annual primary production of particularly woody plant functional types stimulated by climate warming and CO_2 fertilization together with a north-easterly shift of vegetation zones (Wramneby *et al.*, 2010): boreal needle-leaved evergreen coniferous forest replaces tundra and expands into the mountain areas of Fennoscandia. The most dramatic changes in vegetation structure were projected to occur in the Scandes Mountains where the succession progresses from tundra vegetation through deciduous forest to evergreen forest (Wramneby *et al.*, 2010). Another projection for the Barents Region included more plant functional types, particularly various shrub growth forms and plant

communities associated with open ground that are more characteristic of northern regions (Wolf *et al*., 2008). Over the next 100 years, this transient model also projected an increase in the northwards and upwards ranges of boreal needle-leaved evergreen forest and an increase in net primary production and leaf area index. As in the study by Wramneby et al. (2010), shade intolerant broadleaved summergreen trees were projected to extend to higher latitudes and altitudes. However, in contrast to these expected results, shrubs, currently expanding in area in many Arctic locations, were modelled to decrease in extent over the next 100 years after an initial increase (Wolf et al. (2008). This is thought to be a result of displacement by forest at their lower /southern limits and restriction of appropriate land at higher altitudes. Also counter-intuitively, tundra areas increased in the projections. This was a result of changes at the highest latitudes that opened land for colonisation at a rate exceeding displacement of tundra by shrubs in the south. A discrepancy in the model was an overestimation of forest in the Kola Peninsula that cannot be explained by climate alone.

Both studies calculated the magnitude of the effects of vegetation change on biospheric feedbacks to the climate system. These included the negative feedbacks of CO_2 sequestration and increased evapo-transpiration and the positive feedback of decreased albedo (Wramneby *et al*., 2010; Wolf et al., 2010).

Although the models generally agree qualitatively with expectations from historic vegetation changes, recent changes and results of climate change simulation experiments in the field, there are considerable uncertainties in the projected rates of change. Van Bogaert et al. (2010) compared maximum rates of annual projected forest advance of 20 km with the maximum observed rate of 20 m. Furthermore, the models do not yet include vertebrate and invertebrate herbivory, extreme events such as tundra fire and extreme winter warming damage or changes in land use that either reduce the rate of vegetation change or open up niches for rapid change. However, projections suggest increases in the ranges of the autumn and winter moths that have outbreaks in populations resulting in the defoliation of birch forest (Ims reference) and a general increase in the “background” (non-outbreak) invertebrate herbivores that may consume more vegetation than the outbreak species in the longer term (Wolf *et al*., 2008).

28.3.3.2. Antarctica

Regional climate warming and associated environmental changes are expected to both increase the frequency at which new potential colonists arrive in Antarctica (particularly the Antarctic Peninsula region) from lower latitudes, and subsequent probability of their successful establishment (Chown, Lee et al. 2012). However, human-assisted transfers of biota overcome several of the barriers facing natural colonists, including the speed of transfer and avoidance of extreme environments such as altitude or oceans (Barnes *et al*., 2006). Analyses for two remote Southern Ocean islands (Gough Island, Marion Island) have shown that human-assisted introductions may be more important by two orders of magnitude than natural introductions (Frenot, Chown et al. 2005). A broader regional analyses has shown that introduced species can alter native biodiversity through both homogenization and differentiation (Shaw *et al*., 2010).

Anthropogenic introductions of alien species are a major threat to Antarctic terrestrial ecosystems (Convey *et al*., 2009; Hughes and Convey, 2010; Convey, 2011). Climate change is expected to increase the potential for anthropogenic introduction of non-indigenous species to the Antarctic terrestrial areas, which could have devastating consequences to the local biodiversity (Hughes and Convey, 2010; Braun *et al*., 2012). It is also expected to exacerbate the impacts on terrestrial habitats of increasing colonies of recovering whales and seabirds (Convey and Lebouvier 2009; Favero-Longo, Cannone et al. 2011). At present, the majority of non-indigenous species established in the sub- and maritime Antarctic are very restricted in their distributions (Frenot, Chown et al. 2005); however, several are invasive and widely distributed across the region. Climate change could result in increased rate of spread of invasive species through colonisation of areas exposed by glacial retreat, as has occurred at South Georgia (Cook *et al*., 2010) and in the maritime Antarctic (Olech and Chwedorzewska 2011). Biosecurity measures may be needed to help control dispersal of established non-indigenous species to new locations, particularly given the expected increase in human activities in terrestrial areas (Hughes and Convey, 2010; Convey *et al*., 2011). An important gap in understanding is the degree to which climate change (particularly relating to warming and water availability) may facilitate some established non-indigenous species switching to invasive status, (Frenot, Chown et

al. 2005; Convey 2010; Hughes and Convey 2010; Cowan, Chown et al. 2011), which has been shown for the sub-Antarctic (Chown *et al*., 2012).

Across terrestrial ecosystems of much of the Antarctic, and particularly of the Antarctic Peninsula and Scotia arc archipelagoes, current environmental change predictions lie within what is known of the ecophysiological capacities of the affected biota. In these areas further climate amelioration is expected to (as is already being seen) relax constraints on biological activity, leading to increases in biomass and extent of existing communities. At present there is no indication that the magnitude of these environmental changes will surpass any environmental boundaries for these biota, and hence result in any form of limitation of their occurrence from their current distribution (e.g. southwards movement of current northern boundaries). As noted earlier, in particular locations it is possible that specific combinations and synergies between different environmental parameters might result in local limitation.

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic islands, along with the continued increased presence of Antarctic fur seals (see 28.2.3 above) are likely to have far greater importance over the timescale under consideration than are those attributable to climate change itself (Turner *et al*., 2009; Convey and Lebouvier, 2009; Convey, 2010).

28.3.4. Economic Sectors

Projections of the economic costs of climate change impacts for different economic sectors in the Arctic are limited, but current assessments suggest that there will be both economic benefits and costs (Forbes, 2011; SWIPA 2011). Non-Arctic actors are likely to receive most of the benefits from increased shipping and commercial development of renewable and non-renewable resources, while indigenous peoples and local Arctic communities will have a harder time maintaining their way of life (Hovelsrud *et al*., 2011).

Arctic communities are exposed to the effects of climate change thru multiple pathways such as changes in weather (temperature, wind, precipitation), via impacts on the natural systems and from their effects on infrastructure and the food sector. Contributing to the complexity of measuring the future economic effects of climate change is the uncertainty in future predictions and the rapid speed of change, which are linked with the uncertainty of the technological and ecological effects of such change (NorAcia 2010). Communities with the same eco-zone may experience different effects from identical climate-related events because of marked local variations in site, situation, culture and economy (Clark *et al*., 2008).

Economic cost estimates have been made for the case of the Alaska economy, and they suggest that heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries, renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). From the present to 2030, permafrost thawing, amplified flooding and coastal erosion from global warming could add considerably to future costs of public infrastructure in Alaska (SCEIGW 2010). Thawing tundra can cause oil pipelines to buckle and break, causing spills (Epstein et al. 2008).Whether or not there will be these impacts, will depend on the design which may allow for these differential movements (Grosse et al.. 2010). A significant part of Alaska's economy is tourism. Loss of wildlife and habitat, such as spruce tree forests, could lead to a loss of tourism income (NWF 2009). Reductions in seabird and marine mammal populations with unusually warm sea temperatures, and declining salmon harvests could negatively affect tourism, native peoples' way of life, and the Alaskan salmon industry (SCEIGW 2010). It has been estimated that the Shishmaref, Kivalina, and Newtok tribal lands will be unlivable due to storm damage and coastal erosion in a number of years. The cost to re-locate these communities is estimated to be significant (Williams and Hanson, 2007).

28.3.4.1. Fisheries

Predicting the impacts of climate change on future fisheries is difficult because it is unclear whether the responses of marine species observed in the past will continue in the future, and because it is difficult to predict the response of

fisheries to shifts in supply. O'Neill et al. (2010) simulated demand for a composite food commodity under global demographic projections. In dollar terms, food expenditures rise steadily in these scenarios, driven by economic growth and demographic factors of urbanization and population growth. In biophysical terms, population growth alone could account for a 50% increase in seafood demand by 2050 relative to current global production levels (Rice and Garcia, 2011).

Climate change will impact the spatial distribution and catch of some open ocean fisheries in the Barents and Bering Seas (medium certainty). There is strong evidence and considerable data showing links between climate driven shifts in ocean conditions and shifts in the spatial distribution and abundance of commercial species in the Bering and Barents Seas (Mueter and Litzow, 2008; Drinkwater, 2011;Section 28.2.2.2.1). In limited cases, coupled bio-physical models have been used to predict future commercial yield or shifts in fishing locations however these predictions are uncertain (Huse, 2008; Ianelli *et al.*, 2011). Adopting successful strategies for management of Arctic fisheries will be a high priority to ensure that fisheries are managed based on sound science and sustainable harvest practices in the future (Molenaar, 2009). In regions of high yield fisheries, strategies will be needed to modify existing management practices to account for the expected shifts in distribution and abundance of commercial species to prevent overfishing and sustain fishery resources. As discussed in section 28.2.2.1, several North Atlantic commercial fish species exhibited shifts in their spatial distribution and abundance in response to ocean warming (Valdimarsson *et al.*, 2012) which have lead to non-trivial challenges to international fisheries agreements (Arnason, 2012). Techniques are under development to project how harvesters will respond to changing economic, institutional and environmental conditions. These techniques track fishers choices based on revenues and costs associated with targeting a species in a given time and area with a particular gear given projected changes in the abundance and spatial distribution of target species (Haynie and Pfeiffer, 2012). Estimates of future revenues and costs will depend in part on future: demand for fish, global fish markets and trends in aquaculture practices (Merino *et al.*, 2012; Rice and Garcia, 2011). While attempts to project global changes in small pelagic (e.g. anchovy, sardine, capelin and herring) fish markets have been attempted, extending these to larger fish species will be more difficult.

28.3.4.2. Forestry and Farming

A warmer climate is likely to impact access conditions and plant illnesses. In the case of Northern Norway, about half of the arable land area is covered by forest and 40% of it is marsh (Grønlund, 2009). If these areas were to be harnessed for farming, it would be at the cost of forestry production or by drying up the marshlands, which would contribute to more greenhouse emissions. Larger field areas could contribute to land erosion through rainfall and predicted unstable winters, and would likely increase conditions for plant diseases and fungal infections (Grønlund, 2009). If the winter season continues to shorten as a result of climate change (Xu et al. 2013), this would negatively affect access to logging sites. Access is best when frozen ground makes transportation possible in sensitive locations or areas that lack road. If the weather changes when logging has already taken place, sanding of the road may become necessary in order to ensure transportation within a specific timeframe, which carries significant economic costs (Keskitalo, 2008). Impact on the carrying capacity of the ground or road accessibility will thus affect forestry economically. Challenges may include limited storage space for wood (Keskitalo, 2008). A warmer climate may also have positive effects on forestry: In the case of Finland where forestry is of great economic importance, the risk of snow damage to forest is estimated to decrease with about 50% towards the end of the century (Hovelsrud *et al.*, 2011).

28.3.4.3. Infrastructure

Northern safety, security, and environmental integrity are much dependent upon transportation infrastructure. Ice as a provisioning system provides a transportation corridor and a platform for a range of activities and access to food sources (i.e. subsistence hunting and fishing on and around ice, oil and gas development) in the Arctic (Eicken et. al., 2009). While much of the infrastructure in the Arctic, including railways, airports, roads, buildings, communications towers, energy systems, and waste disposal sites for communities, as well as large-scale facilities and waste-containment sites, have been built with weather conditions in mind, much of it remains vulnerable and inadequate to respond to environmental emergencies, natural disasters, and non-environmental accidents

(Governments of Yukon, Northwest Territories, and Nunavut, 2008. A Multi-Modal Transportation Blueprint for the North in National Round Table on the Environment and the Economy 2009, 51; NorAcia 2010).

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much of the infrastructure in the North is dependent upon the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines and provide access to remote communities in the winter. Structures built on ice-rich soils will be more vulnerable to thawing and a changing climate than those built on ice-poor soils or bedrock and impacts are likely to be negligible. Communications towers and energy transmission infrastructure located in remote permafrost areas are becoming increasingly susceptible to the risk of failure and, since accessibility may also be an issue and the cost of redundancy is prohibitive, the threat posed by this hazard will likely become increasingly significant. Energy pipelines built over permafrost could be at risk of rupture and leakage, and warmer temperatures are already resulting in shorter winter road seasons. Failure of frozen-core dams on tailing ponds due to thawing and differential settlement, or thawing of tailings piles associated with climate warming, could in its turn result in contaminants being released into the surrounding environment, causing subsequent disastrous and irreversible degradation of sensitive habitat and human health. In the long term marine and freshwater transportation will need to shift its reliance from ice routes to open-water or land-based transportation systems. Of appropriate community adaptations to the predicted changes relocation is one option to deal with persistent flooding and bank erosion (Furgal C., 2008;National Round Table on the Environment and the Economy 2009).The implications for the sea-ice system may prove to have other major impacts as well, including environmental and socio-economic or geopolitical change which may substantially modify types of services offered and their uses by competing interests. Changing sea-ice (multiyear) conditions are suspected i.e. to have a regulating impact on marine shipping and coastal infrastructure through possible hazards on them (Eicken *et. al*., 2009).

28.3.4.4. Inland Transportation, Communication, and Drinking Water

By adapting transportation models to integrate monthly climate model (CCSM3) predictions of air temperature, combined with datasets on land cover, topography, hydrography, built infrastructure, and locations of human settlements, estimates have been made about changes to inland accessibility for northern landscapes northward of 40ºN by mid-21st Century (Stephenson *et al*., 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000 kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000-2014) for eight circumpolar countries was projected to be -14%, varying from -11 to -82%. In absolute terms, Canada and Russia (both at -13%) account for the majority of declining winter-road potential with ~1x10^6 km^2 being lost.

Climate change impacts have increased the demand for improved communication infrastructure and related services (e.g. cellular and improved citizens band radio (CB) service), and community infrastructure for the safety and confidence in drinking water (National Round Table on the Environment and the Economy 2009). The access, treatment and distribution of drinking water has been and is generally dependent upon a stable platform of permafrost for pond or lake retention, a situation that is currently changing. Several communities have reported the need for more frequent water-quality testing both municipal systems and untreated water sources to ensure its availability (Furgal C., 2008). Demands on infrastructure and building costs is likely to increase with the impact of warming and thawing permafrost.

28.3.4.5. Terrestrial Resource Management (Oil and Gas, Mining, Forestry in the Arctic)

Sea ice retreat and thawing permafrost will have potential direct and indirect impacts on resource exploitation. Longer shipping season and improved access to ports may lead to increased petroleum activities, although possible increased wave activity and coastal erosion may increase costs related to infrastructure and technology. Disappearance of ice roads may restrict onshore exploration activities

The most recent comprehensive assessment of undiscovered petroleum resources is the Circumpolar Arctic Resource Appraisal (CARA) completed in 2008 by US Geological Surveys. The USGS (2008) estimated the Arctic undiscovered petroleum resources to 413 billion barrels of oil equivalents (bboe), about 22 per cent of global undiscovered conventional oil and gas resources. The share of oil (including natural gas liquids) was estimated to 134 bboe (15 per cent of global oil resources) and 279 bboe of gas (30 per cent of global resources). Hence the Arctic contains vast resources of oil, which is hard to replace as transportation fuel, and vast resources of gas, a more climate benign fuel than coal. The petroleum resources are unevenly distributed among Arctic regions and states. Figure 28-5 shows the allocation of oil and gas on regions. Arctic Russia is the major petroleum region with about 40 per cent of total Arctic oil and 70 per cent of total Arctic gas resources. Alaska is second with 28 per cent of oil and 14 per cent of gas.

[INSERT FIGURE 28-5 HERE
Figure 28-5: (top) Regional distribution of Arctic undiscovered oil resources (including NGL), and (bottom) regional distribution of Arctic undiscovered natural gas resources (including NGL). Source: Statistics Norway, 2010.]

The USGS 2008 study revised its assessments with respect to regional resource allocation compared with its own 2000 assessment. USGS (2008) lowered their estimates for oil resources in Norway, Greenland and Russia and raised the estimates for Alaska and Canada. Gas estimates were lowered for Norway and raised for all other regions. For the Arctic as a whole, USGS (2008) assessed the undiscovered petroleum resources to 8.5 per cent below their previous estimate (USGS 2000), whereas Wood Mackenzie (2006) estimated petroleum resources at only 40 per cent of the USGS (2008). These different estimates illustrate the considerable uncertainty on the level of resources in the Arctic.

Tables 28-1 and 28-2 show arctic oil and gas production by 2010 and their share in global supply.

[INSERT TABLE 28-1 HERE
Table 28-1: Arctic oil production in relation to non-OPEC and global supply, reference scenario (%).]

[INSERT TABLE 28-2 HERE
Table 28-2: Arctic gas in relation to MENA and global supply, reference scenario (%).]

Arctic Russia and Alaska are the major producers of oil. Greenland has a large potential, but not yet any production.

The Arctic is also rich in other natural resources, such as minerals and fish. Figure 28-6 Illustrates the dominant contribution of natural resource based industries to regional GDP in the Arctic (2005)

[INSERT FIGURE 28-6 HERE
Figure 28-6: Value added in natural resource-based industries in Arctic regions, 2005 (% of regional GDP). Source: Statistics Norway, 2010.]

In Arctic Russia the extraction of energy alone contributes close to 60 per cent of regional GDP (see Figure 28-7). In Alaska and Arctic Canada the energy and minerals contribute 30-38 per cent, whereas fishing and fish processing are the major elements in Faroe Islands, Greenland and Iceland.

[INSERT FIGURE 28-7 HERE
Figure 28-7: (a) Arctic gas production, reference scenario (Mtoe); and (b) regional distribution of West Arctic gas production, reference scenario (Mtoe). Source: Statistics Norway, 2010.]

Among indirect impacts on resource exploitation are changes related to changing ecosystems and changes in distribution and abundance of species. This may lead to stricter environmental regulations and requirements (e.g. AMAP. Oil and Gas Activities in the Arctic 2007). Conservation management and protected areas designed to address the effects of human actions are well developed and extensive in the Arctic.

28.3.4.6. Anticipated New Resource Exploitation Development in the North

GCMs generally underestimate the duration of the ice-free period in the Arctic Ocean and simulate slower changes than those observed in the past decades (Stroeve *et al.*, 2007). Mokhow and Khon (2008) used a sub-set of climate models that better than other GCMs reproduce the observed sea ice dynamics to project the duration of the navigation season along the NSR and through NWP under the moderate SRES-A1B emission scenario. According to their results, by the end of the 21st century NSR may be open for navigation 4.5±1.3 months per year, while the NWP may be open 2-4 months per year (Figure 28-8). The models did not predict any noticeable changes of the ice conditions in the NWP until the early 2030s.

[INSERT FIGURE 28-8 HERE
Figure 28-8: Projected duration of the navigation period (days) over the North-West passage (1) and Northern Sea route (2). Source: Mokhow and Khon, 2008.]

Analysis indicated that by the end of the 21st century transportation costs from Europe to Asia along the NSR may be up to 15% less than the transit through Suez Canal (Mokhow and Khon 2008). Apart from the less restrictive requirements to the ice class of cargo vessels and decreased demand for ice-breaker's support due to longer open water season this will stimulate the development of the navigation along the NSR and in the longer term also through NWP (Peresypkin and Yakovlev, 2007 from Mokhow and Khon), although in the following two decades commercial shipping in the NWP is unlikely.

Three active proposals for arctic submarine fiber optic cables connecting Eastern Asia with Europe - one through the NSR and two through the NWP and all planned to be in operation before 2015- illustrate the non-shipping uses for sea routes that are being made possible by seasonal ice free periods and which will require at least periodic access for maintenance. (Source: http://www.extremetech.com/extreme/122989-1-5-billion-the-cost-of-cutting-london-toyko-latency-by-60ms).

28.4. Adaptation in the Polar Regions

There is general agreement that both indigenous and non-indigenous people in the Arctic have a long history of adapting to natural variability in climate and the natural resource base, as well as in recent decades rapid socio-economic, cultural and technological change (Forbes and Stammler, 2009; Wenzel, 2009; West and Hovelsrud, 2010; Ford and Pearce, 2010; Bolton *et al.*, 2011). Climate change exacerbates the existing stresses faced by Arctic communities (Rybråten and Hovelsrud, 2010; Crate and Nuttall, 2009), and is only one of many important factors influencing adaptation (Berrang-Ford *et al.*, 2011). Climate adaptation needs to be seen in the context of these inter-connected and mutually reinforcing factors (Tyler *et al.*, 2007; Hovelsrud and Smit, 2010). The complex inter-linkages between societal, economic, political factors and climatic change represent unprecedented challenges for northern communities (Ford *et al.*, 2010; Hovelsrud *et al.*, 2011; Keskitalo, et al 2010; Abele et al., 2009).
There is considerable evidence that changing weather patterns, declining sea-ice, thawing permafrost, and plant and animal species' abundance and composition have consequences for the wellbeing of communities in the Arctic (see 28.2.5.2 and 28.3.4). Sea-ice is particularly important for coastal communities which rely upon it for transportation between communities and hunting areas (Krupnik et al., 2010). Changing the duration and conditions of sea ice and the consequent changes to country food availability significantly impact the wellbeing of communities (Furgal and Seguin, 2006; Ford and Berrang-Ford, 2009; Ford *et al.*, 2010), outdoor tourism (Dawson *et al.*, 2010) and hunting and fishing (Wiig *et al.*, 2008; Brander, 2010).

Adaptation to climate change is taking place at the local and regional levels where the impacts are often felt most acutely and the resources most readily available (Hovelsrud and Smit, 2010). Such adaptation is often taking place despite the lack of national guidelines (Dannevig *et al.*, 2012; Juhola et al., 2012; Glaas et al., 2010). Current experiences and projections of future conditions often lead to technological adaptation responses such as flood and water management and snow avalanche protection (West and Hovelsrud, 2010; Hovelsrud and Smit, 2010) rather than policy responses (Hedensted Lund et al., 2012; Rudberg et al., 2012). Climate variability and extreme events,

such as floods, avalanches and mud slides, are found to be salient drivers of adaptation (Berrang-Ford *et al.*, 2011; Dannevig *et al.*, 2012; Amundsen et al., 2010).

National policies for adaptation are largely in their infancy in the Arctic (Keskitalo 2010a,b; Berrang-Ford et al., 2011; Yamineva 2012). The lack of local scale climate projections, combined with uncertainties in future economic, social and technological developments often act as barriers to adaptation. These barriers, together with other societal determinants such as ethics, cultures, and attitudes towards risk may cause inaction (Adger *et al.*, 2009; West and Hovelsrud, 2010). Resolving divergent values across and within different communities poses a challenge for the increasingly complex societies and governance regimes. A determining factor in building adaptive capacity is the flexibility of enabling institutions to develop robust options (Keskitalo et al., 2009; Hovelsrud and Smit 2010; Forbes et al. 2009; Ford and Goldhar, 2012). In the North American and Scandinavian context, adaptive co-management responses have been developed through land claims settlements and/or multi-scale institutional cooperation to foster social learning (Berkes, 2009; Armitage et al., 2008).

28.4.1. Adaptation and Indigenous Peoples

The adaptive capacity of Arctic indigenous peoples is largely due to an extensive traditional knowledge and cultural repertoire, and flexible social networks (see Chapter 12, section 12.3). The dynamic nature of traditional knowledge is valuable for adapting to current conditions (Tyler et al., 2007; Eira et al., 2012). The sharing of knowledge ensures rapid responses to crises (Ford et. al., 2007). In addition, cultural values such as patience, persistence, calmness, respect for elders and the environment are important for adaptation. Some studies suggest that traditional knowledge may not always be sufficient to meet rapid changes in climate and weather, or extreme events (see also Chapter 12), and it may be perceived to be less reliable because the changing conditions are beyond the current knowledge range (Ingram et al., 2002; Ford et al., 2006; Valdivia et al., 2010; Hovelsrud et al., 2010a). This has in some cases created a sense of a “loss of order in the world” (Turner et al., 2008,) and less confidence in the reliability of knowledge keepers (Chapin III et al., 2006; Hovelsrud and Smit, 2010).

Over the last half-century, the adaptive capacity in some indigenous communities has been challenged by the transition from semi-nomadic hunting groups to permanent settlements (Ford et al, 2010). Forced or voluntary migration as an adaptation response can have deep cultural impacts. The establishment of permanent communities can also led to increasing employment opportunities and income diversification for indigenous peoples, which in turn may cause social inequalities (Ford et al, 2010). However, the current level of skilled labour and formal education may limit the abilities to take advantage of such opportunities (Furgal C., 2008). On the other hand the intergenerational transfers of knowledge and skills through school curricula, land camps, and involvement in community-based monitoring programmes may strengthen adaptive capacity (Bolton et al., 2011; Hovelsrud and Smit, 2010; Ford et. al., 2007; Forbes 2007).

Renewable resource harvesting remains a significant component of Arctic livelihoods and with climate change hunting and fishing has become a riskier undertaking, and many communities are already adapting in a reactive manner (Gearheard *et al.*, 2011; Laidler *et al.*, 2011). Adaptation includes taking more supplies when hunting; constructing more permanent shelters on land as refuges from storms; improved communications infrastructure; greater use of global positioning systems (GPS) for navigation; synthetic aperture radar (SAR) to provide estimates of sea-ice conditions (Laidler *et al.*, 2011) and the use of larger or faster vehicles (Ford et al, 2010). Avoiding dangerous terrain can result in longer and time-consuming journeys which can be inconvenient to those with wage-earning employment (Ford et.al. 2007).

Reindeer herders have developed a wide range of adaptation strategies in response to changing pasture conditions. These include: moving herds to better pastures (Bartsch *et al.*, 2010); providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009); retaining a few castrated reindeer males to break through heavy ice-crust (Reinert et al., 2008); ensuring an optimal herd size (Forbes et al., 2009; Tyler et al., 2007); and creating multicultural initiatives combining traditional knowledge with scientific studies to create and distribute co-produced dataset (Vuojala-Magga *et al.*, 2011; Bongo *et al.*, 2012). Coastal fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud et al., 2010b).

In some Arctic countries indigenous peoples have successfully negotiated land claims rights and have become key players in addressing climate change, as well as other issues related to education, health-care and economic development (Abele et al., 2009). In some instances this has given rise to tensions over land/water use between traditional livelihoods (e.g. reindeer herding, marine mammal hunting) and new opportunities (e.g. tourism and natural resource development) (Forbes, 2006; Hovelsrud and Smit, 2010). Some territorial governments in Northern Canada promote adaptation by providing hunter support programs (Ford et al., 2006; Ford et. al., 2010).

The health of many indigenous peoples is being affected by the interactions of changes in the climate with ongoing changes in human, economic and biophysical systems (Donaldson et al., 2010). The distribution of traditional foods between communities and the use of community freezers in the Canadian Arctic has improved food security, an important factor for health (Ford et al, 2010). While wage employment may enhance the possibilities for adaptive capacity, greater involvement in full time jobs can threaten social and cultural social cohesion and mental well-being by disrupting the traditional cycle of land-based practices (Berner et al., 2005; Furgal, 2008).

28.4.2. Adaptation and Industrial Development

Increasing access to minerals and fossil fuels and increased shipping, due to reduced sea ice, will bring both opportunities and challenges. The extraction of off-shore fossil fuels in areas where icebergs are a significant threat will require design changes to drilling platforms (McClintock et al, 2007). Some of the resources that will be extracted are expected to be transported by ship to southern markets; other resources may be transported by pipelines whose design requirements will need to take climate change into account. On shore processing plants and particularly waste containment facilities must be able to maintain their structural integrity over the expected long lifetime of a project (Prowse et al, 2009). Unless mines are located close to the coast and port facilities, resupply is generally limited to winter periods and the availability of ice roads, whereas exploration activities are usually restricted to short summer periods with access by air.

_____ START BOX 28-1 HERE _____

Box 28-1. Adapting Critical Infrastructure to Climate Change in Northern Canada

Climate change is increasingly recognized as a critical factor in the design of major infrastructure projects in northern Canada and has been incorporated in environmental impact assessments since the late 1990's (Hayley and Horne, 2008). A risk-based project screening tool has been developed for considering climate change in northern engineered facilities (CEAA, 2003). A study by Canada's National Roundtable on the Environment and the Economy (Government of Canada, 2009) reviewed the use of existing policy tools such as codes and standards, insurance and emergency/disaster management to support wise adaptation of critical infrastructure. The study concluded that there was inadequate technical (including monitoring) information and capacity as well as a systematic assessment of risks to take full advantage of these policy tools. This was in part because of limited interaction between scientists and decision-makers. The lack of systematic assessments meant that often there was unclear responsibility for infrastructure investment and operational decisions.

Adaptation of northern infrastructure to thawing permafrost will largely involve current solutions to reduce the impacts of ground disturbance (CSA, 2010). These include the use of pile foundations (that may need to be deeper to account for climate change), insulation of the surface (which may require thicker gravel pads), clearance of snow (to promote colder winter ground temperatures), adjustable foundations for smaller structures and increased use of artificial cooling with heat-pumps and thermosyphons to ensure that foundation soils remain frozen. Recently developed techniques, such as air-convection embankments may also be utilized. Where permafrost is thin, frozen ice-rich material may be excavated and replaced with thaw-stable material, or intentionally thawed by clearing vegetation and postponing construction for several years until the permafrost has completely degraded and the ground has settled. Finally, a critical adaptive response will be monitoring infrastructure performance; determine if changes in permafrost conditions deviate from those predicted; and decide whether additional adaptation measures are required (Burgess, et al, 2010).

Ice roads and ice bridges that are constructed and maintained each winter provide a relatively inexpensive way to supply northern communities and industry, particularly the rapidly expanding oil/gas and mining sector. In addition, these ice-roads link communities and facilitate social and cultural activities, and provide access to hunting, fishing, or trapping areas (Furgal and Prowse, 2008; Ford et al., 2008).

_____ END BOX 28-1 HERE _____

28.5. Arctic Pollution and Climate Change

Recent studies suggest that transport pathways, intercompartmental distribution, bioaccumulation and transformation of environmental contaminants such as persistent organic pollutants (POPs), mercury (Hg) and radionuclides in the Arctic and the globe as such may be affected by climate change (AMAP 2011, UNEP/AMAP 2011). Ambient temperature variability and temperature gradients directly affect the volatilization, remobilization, and transport pathways of mercury and POPs in the atmosphere, ocean currents, sea ice and rivers. Thus, the rate and efficacy of transport of these contaminants into the Arctic and their occurrence in the environment are expected to be significantly affected by climate change (Macdonald and Loseto, 2010; AMAP 2011).

An oxidized form of gaseous mercury in the Arctic atmosphere is deposited on ice and snow surfaces in episodic atmospheric mercury depletion events (AMDEs). The oxidation is enhanced by photochemical reactions involving halogens released from freezing sea ice. The extent of sea ice and changes in the timing of freezing will affect AMDE dynamics and the deposition of mercury in the Arctic (Steffen *et al*., 2007).

The fate of POPs and mercury in the terrestrial environment is mainly controlled by temperature and biogeochemical processes (Teng *et al*., 2012; AMAP 2011). Changes in the carbon cycle by thawing permafrost will affect the methylation of mercury and the bioaccumulation and release of POPs. Ma et al. (2011) and Hung et al. (2010) demonstrated that POPs are already being remobilized into the air from sinks in the Arctic region as a result of decreasing sea ice and increasing temperatures.

There is evidence that climate change will cause alterations in trophic structures, food sources and migratory patterns, which may influence bioaccumulation and biomagnification of some POPs. There is also concern about effects from multiple stressors, including exposure to POPs and climate change, in environments such as the Arctic where species are living at the edge of their physiological tolerance (Macdonald *et al*., 2005; Borgå *et al*., 2010; Teng *et al*., 2012; UNEP/AMAP 2011).

There is *high confidence* that climate change will affect the fate and impacts of anthropogenic contaminants in the Arctic, but the extent to which this will occur is uncertain.

28.6. Research and Data Gaps

Our understanding of a region of the globe as large and heterogeneous as the Polar Regions and with multiple human and development stresses is still imperfect. For example, ice-sheets in Greenland and Antarctica and sea-ice in the Arctic are declining faster than models predict. Many of the physical and biological systems in the Polar Regions are sensitive to rapid change and could tip into new regimes as they cross critical thresholds. Systematic monitoring will be essential for the early detection of these changes and remote-sensing will be particularly valuable in providing geographically comprehensive coverage.

Increasing evidence indicates that changes in the Polar Regions are having impacts on global-scale physical and human systems. These include: effects on the global climate system via changes in thermohaline and atmospheric circulation; the enhanced release of greenhouse gases, such as from land and ocean based sources of methane and carbon; and intensification of natural-resource exploitation and expansion of international trade. Understanding these changes will require international and interdisciplinary collaboration.

The combined effects of climate-change, globalization and other stresses are producing impacts on northern residents and these also need to be carefully monitored so there is adequate and relevant information for developing appropriate adaptation measures and policies such as new regulations governing infrastructure design and natural resource harvesting. Although there is a considerable body of traditional and western experience in adapting to changing climate and resource availability this may be inadequate if the magnitude and rate of the change is greater than in the past. Mechanisms will be required to develop, share and evaluate adaptation response options.

Frequently Asked Questions

FAQ 28.1: What will be the net socio-economic impacts of change in the Polar Regions?

Climate change will have cost and benefits for Polar Regions. In the Arctic, positive impacts include new possibilities for economic diversification, marine shipping, agricultural production, and forestry. Northern Sea Route is predicted to have up to 125 days per year suitable for navigation by 2050, while the heating energy demand in the populated Arctic areas is predicted decline by 15%. In addition, there could be greater accessibility to offshore mineral and energy resources although challenges related to environmental impacts as well as effects on traditional livelihoods of northern residents are possible. Changing sea ice condition and permafrost thawing may cause damage to installations such as bridges, pipelines, drilling platforms, hydropower and other infrastructure. This poses major economic costs and human risks, although these impacts are closely linked to the design of the structure. Furthermore, warmer winter temperatures will shorten the accessibility of ice roads that are critical for communications between settlements and economic development. Since 1970s maximum ice thickness decreased up to 15 cm in rivers within Siberia. Statistically, a long-term mean increase of 2 to 3°C in autumn and spring air temperature produces an approximate 10 to 15 day delay in freeze-up and advance in break-up, respectively. As a result, many of the ice roads may become less viable option than the all-weather roads with implications for significantly increased costs. Particular concerns are associated with projected increase in the frequency (by 20-50% in the coming decade) and severity (with 35 to 60% increase in peak break-up water levels) ice-jam floods on Siberian rivers. They may have potentially catastrophic consequences for the villages and cities located in the river plain, as exemplified by the 2001 Lena River flood, which demolished most of the buildings in the city of Lensk. Climatic, accecerbated by other large-scale changes can have potentially large effects on Arctic communities, where relatively simple economies leave a narrower range of adaptive choices. Changing sea ice conditions will impact indigenous livelihoods, and changes in resources, including marine mammals, could represent a significant economic loss for many local communities. Food security and health and well-being are expected to be impacted negatively. In the Antarctic, tourism is expected to increase, and risks exist of accidental pollution from maritime accidents, and an increasing likelihood of introductions of alien species to terrestrial environments. Fishing for Antarctic krill near to the Antarctic continent is expected to become more common during winter months in areas where winter sea ice extent reduces.

FAQ 28.2: Why are changes in sea ice so important?

Sea ice is a dominant feature of Polar Oceans. Shifts in the distribution and extent of sea ice during the growing season impacts the duration, magnitude and species composition of primary and secondary production in the Polar Regions. With less sea ice many marine ecosystems will be experiencing shifts from light limitation to nutrient limitations as well as shifting balance between the primary production by ice algae and phytoplankton with implications for Arctic food webs. Sea ice is also an important habitat for juvenile Antarctic krill, providing food and protection from predators. While the overall sea ice extent in the Southern Ocean has not changed markedly in recent decades, there have been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc. Changes in sea ice will have bottom up consequences for marine foodwebs. Mammals and birds utilize sea ice as haul-outs during foraging trips (seals, walrus, and polar bears in the Arctic and seals and penguins in the Antarctic). Some seals (e.g. Bearded seals in the Arctic and crabeater and leopard seals in the Antarctic) give birth and nurse pups in pack ice. Shifts in the spatial distribution and extent of sea ice will alter the spatial overlap of predators and their prey. According to model projections, within 50-70 years loss of hunting habitats may lead to extirpation of the polar bears from seasonally ice-covered areas, where currently two thirds of their world population live. The vulnerability of marine species to changes in sea ice will depend on the exposure to change, the sensitivity of the

species to changing environmental conditions and adaptive capacity of each species. More open waters and longer ice-free period in the northern seas enhance the effect of wave action and coastral erosion with implications for coastal communities and infrastructure.

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Table 28-1: Arctic oil production in relation to non-OPEC and global supply, reference scenario (%).

	2010	2050
Arctic share of Non-OPEC conventional oil	16	31
Arctic share of total Non-OPEC	16	22
Arctic share of world oil production	10	8

Table 28-2: Arctic gas in relation to MENA and global supply, reference scenario (%).

	2010	2050
Arctic share of total production outside Middle East/North-Africa (MENA)	27	22
Arctic share of world gas production	22	10

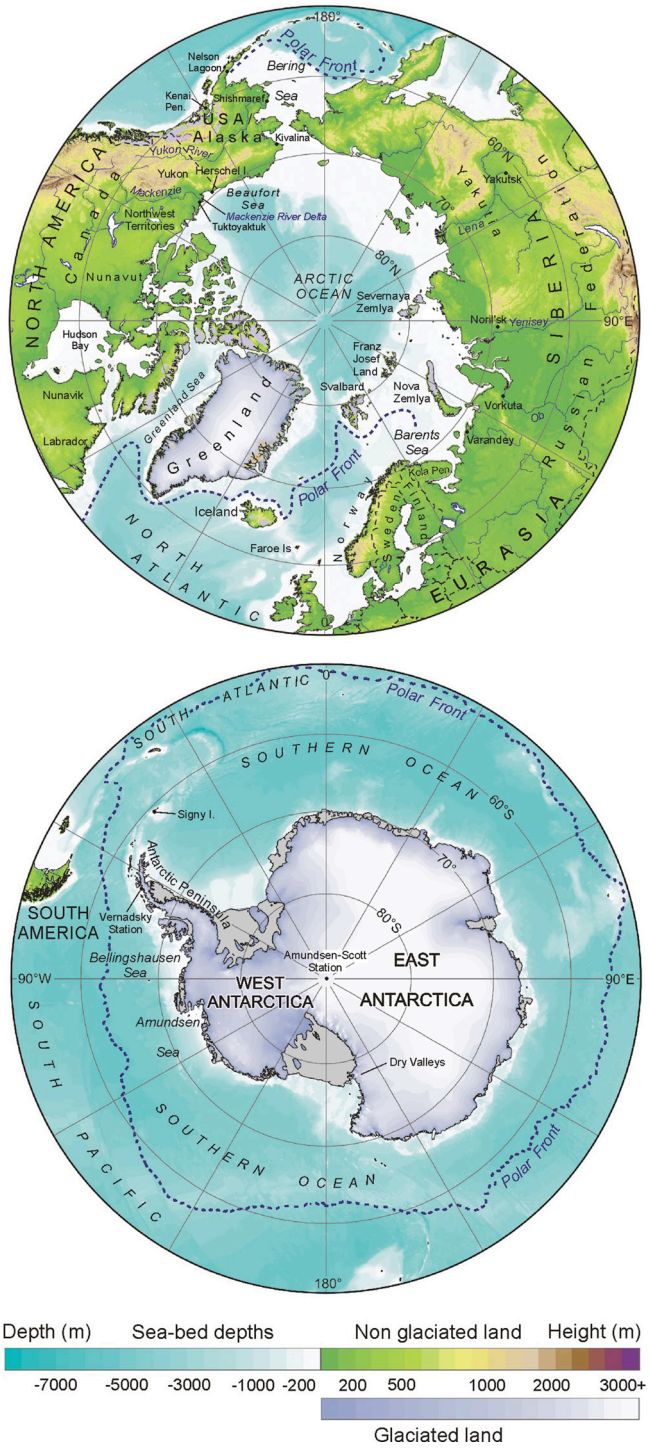


Figure 28-1: Location maps of the North and South polar regions. Source: IPCC, 2007.
[Note: WGII AR4 Figure 15.1 to be updated, including the addition of major currents. Credit: P. Fretwell, British Antarctic Survey.]

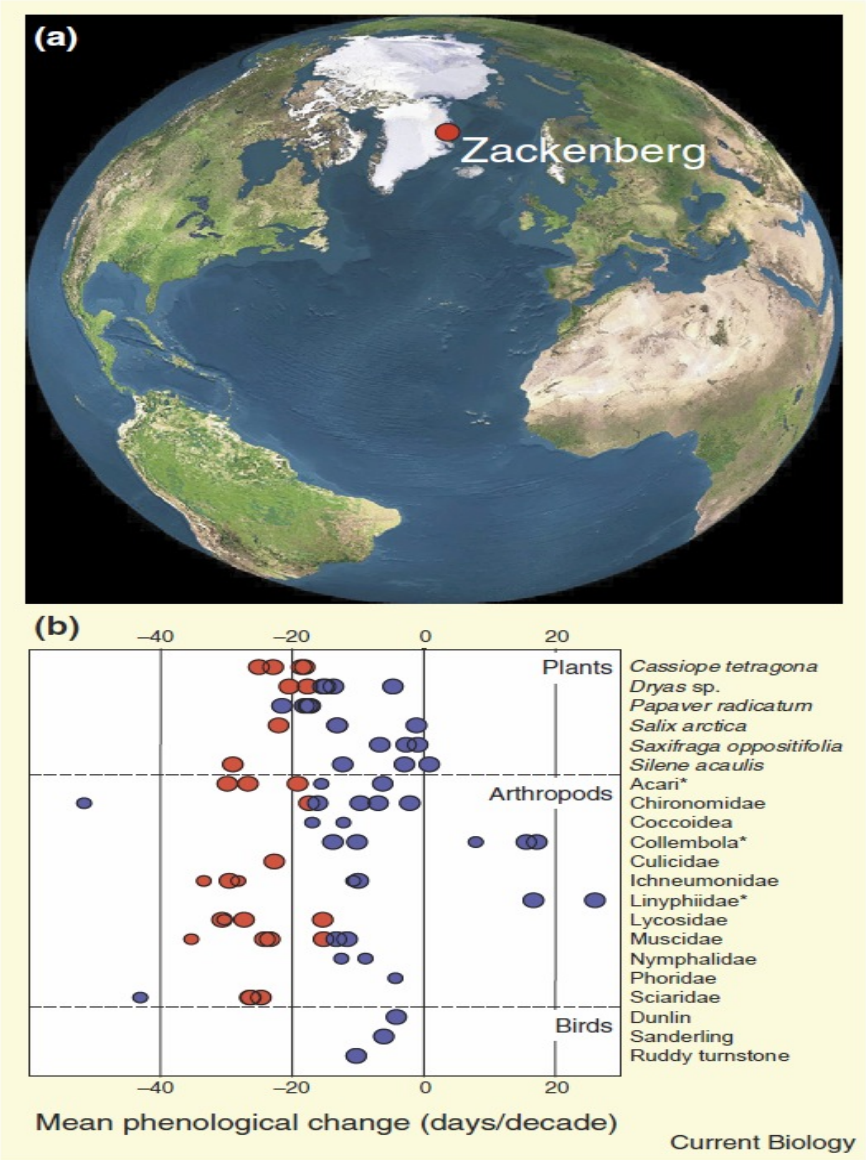


Figure 28-2: Advancement of phenological events in high-Arctic Greenland. a) location of the study area Zackenberg, North-east Greenland. b) Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initation dates (birds). Red dots are statistically significant, blue dots are not (Høye *et al.*, 2007).

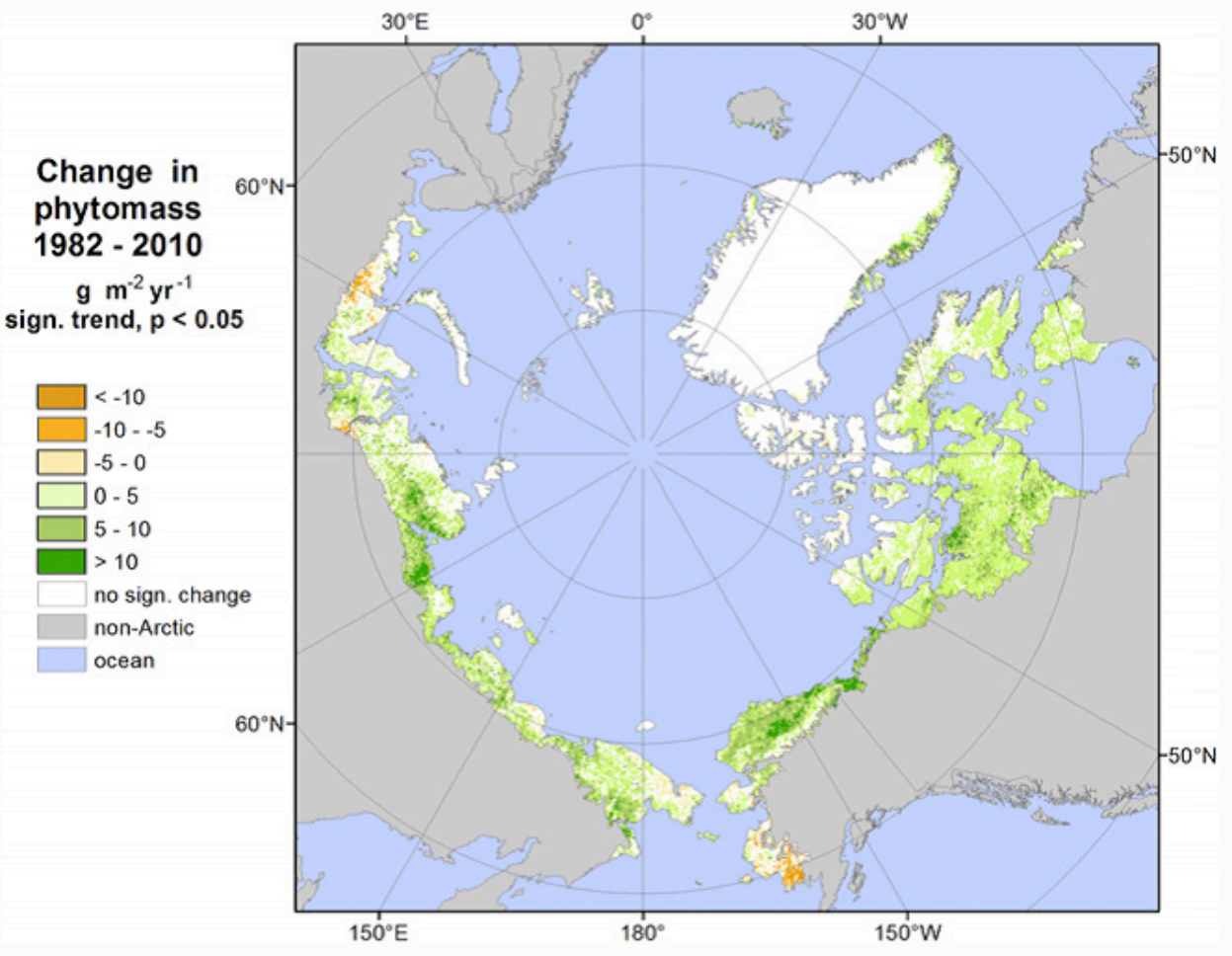


Figure 28-3: Significant changes (p < 0:05) in aboveground tundra phytomass from 1982 to 2010 (Epstein et al. 2012).

Figure 28-4: Fishing vessel activity. Source: AMSA, _____.

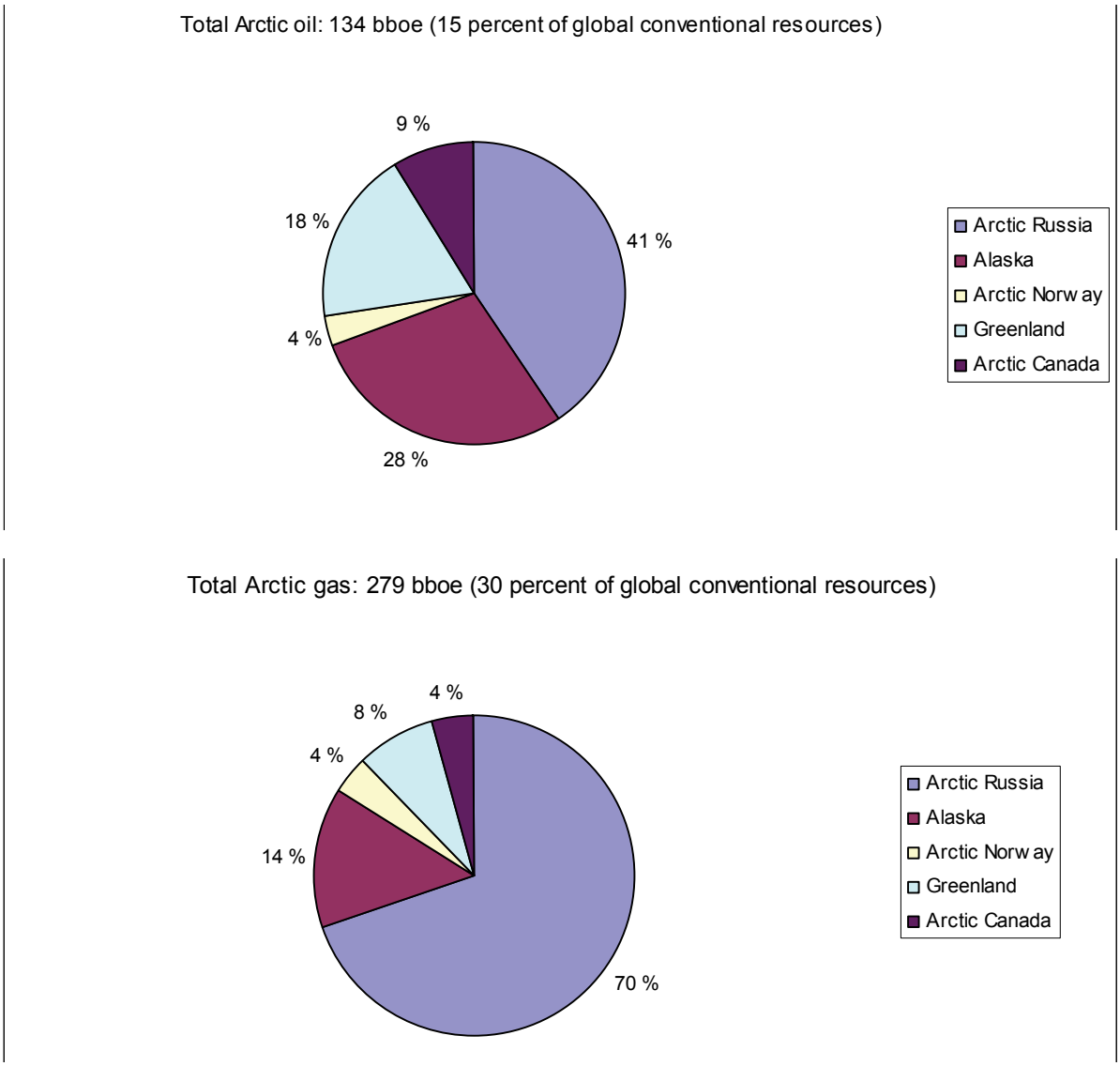


Figure 28-5: (top) Regional distribution of Arctic undiscovered oil resources (including NGL), and (bottom) regional distribution of Arctic undiscovered natural gas resources (including NGL). Source: Statistics Norway, 2010.

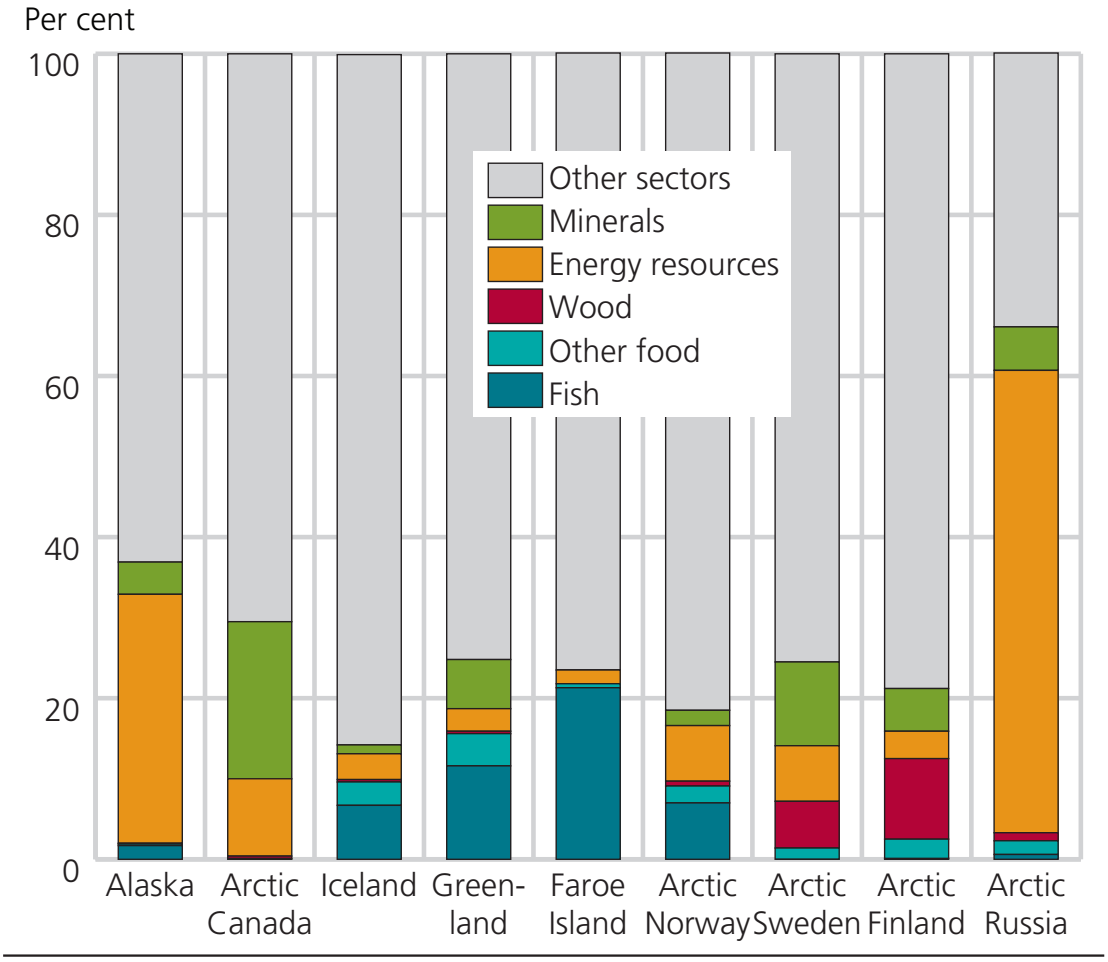
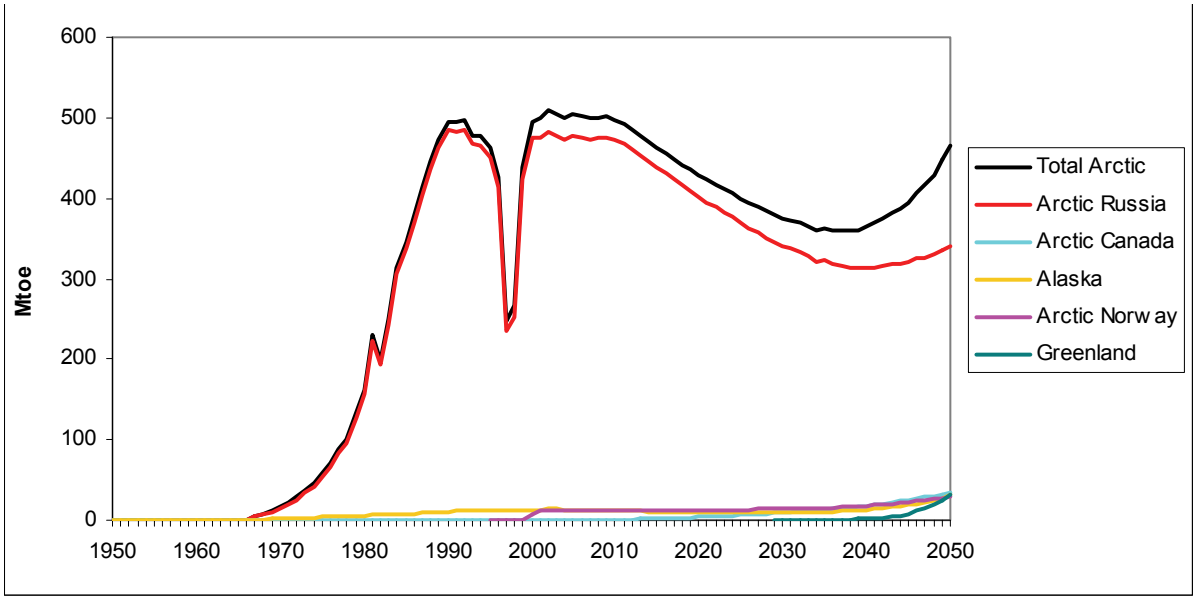


Figure 28-6: Value added in natural resource-based industries in Arctic regions, 2005 (% of regional GDP). Source: Statistics Norway, 2010. [TO BE UPDATED]

a)



b)

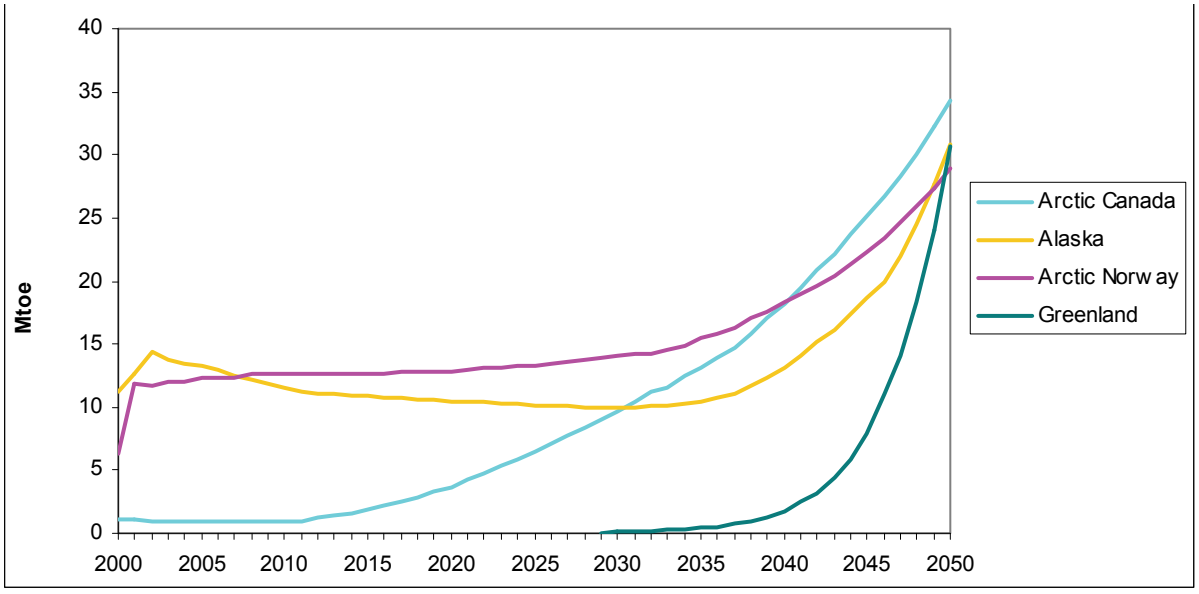


Figure 28-7: (a) Arctic gas production, reference scenario (Mtoe); and (b) regional distribution of West Arctic gas production, reference scenario (Mtoe). Source: Statistics Norway, 2010.

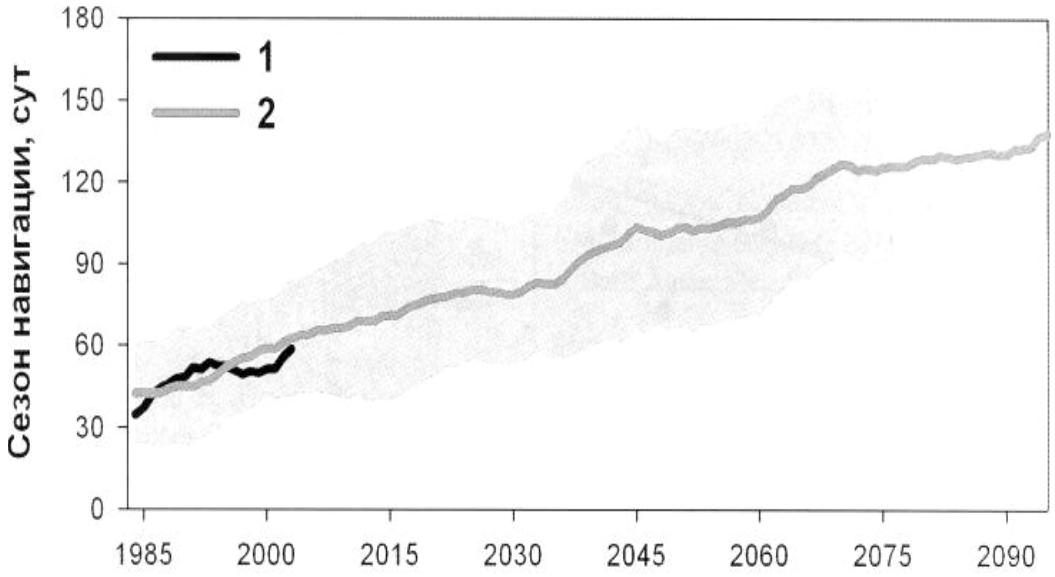


Figure 28-8: Projected duration of the navigation period (days) over the North-West passage (1) and Northern Sea route (2). Source: Mokhow and Khon, 2008.

Chapter 29. Small Islands

Coordinating Lead Authors
Leonard Nurse (Barbados), Roger McLean (Australia)

Lead Authors
John Agard (Trinidad and Tobago), Lino Pascal Briguglio (Malta), Virginie Duvat-Magnan (France), Netatua Pelesikoti (Samoa), Emma Tompkins (UK), Arthur Webb (Fiji)

Contributing Authors
John Campbell (New Zealand), Dave Chadee (Trinidad and Tobago), Shobha Maharaj (Trinidad and Tobago), Rolph Payet (Seychelles), Daniel Scott (Canada)

Review Editors
Thomas Spencer (UK), Kazuya Yasuhara (Japan)

Volunteer Chapter Scientist
Veronique Morin (Canada)

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References

Executive Summary

The distinction between *observed* and *projected* impacts of climate change is often not clear in the literature on small islands (*high agreement*). Many publications deal with both types of impact, often using a recent 'observed' impact relating to some extreme weather- climate- or ocean-related event as an analogy to what may happen in the future. Moreover, much of the literature on projected climate change impacts on small islands is not specific about the scenario (s) used, partly because of the difficulty in moving from global-scale scenarios and models to the scale of small islands. [29.4] Consequently, there is *low confidence* in the magnitude of projected impacts in some sectors and systems of small islands. However, there is evidence that this challenge can be partly overcome with continued improvements in downscaling, as is demonstrated by the use of downscaled SRES scenarios in a comprehensive assessment of the vulnerability of fisheries in 22 Pacific island countries. As these and other studies are duplicated elsewhere, confidence in projected impacts of climate change on small islands will increase. [29.3, 29.4.2]

Many impacts on small islands are generated from processes well beyond the borders of an individual nation or island and generally they have negative effects (*high confidence, robust evidence).* Trans-boundary impacts on small islands may originate in distant regions including continental countries and high latitudes. Examples of the former include airborne dust from the Sahara and Asia reaching small islands far down-drift from the desert source, and examples of the latter include large ocean swells generated by extra tropical cyclones and high latitude low pressure systems. [29.5.1, 29.5.2] Other trans-boundary impacts result from invasive plant and animal species that reach the warmth of tropical small islands and the spread of aquatic pathogens that may have implications for human health. For island communities the trans-boundary implications of existing and future 'invasions' and human health challenges are projected to increase in a changing climate. [29.3.3.2, 29.5.3, 29.5.5]

For most small islands climate change is just one of a series of multiple stresses that must be coped with, and often it is not the most important one *(medium agreement, medium confidence*). Increasingly there are arguments that priority in the short-term should be given to addressing immediate development problems such as water supply, waste management, deteriorating ecosystems and food security. [29.3.3] We agree that addressing the critical social, economic and environmental issues of the day will *likely* increase human and environmental resilience to the longer-term impacts of climate change. [29.6.1, 29.6.2.3, Figure 29-5]

Adaptation and mitigation on small islands are not trade-offs, but can be regarded as complementary components in the response to climate change (*medium confidence).* At least three key areas for adaptation-mitigation inter-linkages in small islands are identified here: energy supply and use, tourism infrastructure and activities, and coastal wetlands. The alignment of these sectors for potential emission reductions together with adaptation needs offers co-benefits and opportunities in small islands. [29.7.2, 29.8] Lessons learned from adaptation and mitigation experiences in one island may offer some guidance to other small island states, though we have *low confidence* in the wholesale transfer of adaptation and mitigation options when the lenses through which they are viewed differ from one island state to the next, based on cultural, socio-economic, ecological and political values. [29.6.2, 29.8]

Assistance from the international community is vital for supporting adaptation and mitigation programs in small islands, though there is increasing concern that some types of interventions may be maladaptive (*medium evidence*). Caution is needed to ensure that donors are not driving the climate change agenda in small islands, as there is a risk that donor-driven adaptation and mitigation aid may not address the critical challenges confronting island governments and communities, and may not be aligned with the sustainable development goals of small islands (*high agreement*). This may lead to inadequate adaptation or a waste of scarce resources and may unintentionally cause enhanced vulnerability by supporting inappropriate adaptation strategies that are externally derived, rather than optimizing the benefits of local practices that have proven to be efficacious through time. [29.8, Box 29-1, 29.6.2.3, 29.6.3]

Island vulnerability to climate change may be related to the experience and perceptions of islanders to both climate and non-climate stressors (*medium agreement*). Islands and islanders are recognized for their long experience of adapting to a range of hazards including extreme weather-climate- and ocean-related events and for their resilience in coping with such hazards. We have *medium confidence* that adaptive capacity is better when the frequency of hazards is greater, but there may be limits to this capacity when small islands are going through rapid socio-economic change. [29.3.3.1, 29.6.1, 29.6.2]

29.1. Introduction

It has long been recognized that greenhouse gas emissions from small islands are negligible in relation to global emissions, but that the threats of climate change and sea-level rise to small islands are very real. Indeed, it has been suggested that the very existence of some atoll nations are threatened by rising sea levels associated with global warming. Whilst such extreme scenarios are not applicable to all small island nations, there is no doubt that on the whole the impacts of climate change on small islands will have serious negative effects especially on socio-economic conditions and bio-physical resources – although impacts will be ameliorated by the extent and effectiveness of adaptation.

The small islands considered in this chapter are principally sovereign states and territories located within the tropics of the southern and western Pacific Ocean, central and western Indian Ocean, the Caribbean Sea, and the eastern Atlantic off the coast of west Africa, as well as in the more temperate Mediterranean Sea.

Although these small islands nations are by no means homogenous politically, socially, or culturally, or in terms of physical size and character or economic development, there has been a tendency to generalise about the potential impacts on small islands and their adaptive capacity. In this chapter we attempt to strike a balance between identifying the differences between small islands as well as recognising that small islands tend to share a number of common characteristics that have distinguished them as a particular group in international affairs. Also in this chapter we reiterate some of the frequently voiced and key concerns relating to climate change impacts, vulnerability and adaptation whilst emphasising a number of additional themes that have emerged in the literature on small islands since the IPCC Fourth Assessment. These include the relationship between climate change policy, activities and development issues; externally generated trans-boundary impacts; and the implications of risk in relation to adaptation and the adaptive capacity of small island nations.

29.2. Major Conclusions from Previous Assessments

Small islands were not given a separate chapter in the IPCC First Assessment (FAR) in1990 though they were discussed in the chapter on 'World Oceans and Coastal Zones' (Tsyban *et al*., 1990). Two points were highlighted. First, that a 30-50 cm sea-level rise projected by 2050 would threaten low islands, and that a 1 m rise by 2100 'would render some island countries uninhabitable' (Tegart *et al*., 1990: 4). Second, the costs of protection works to combat sea-level rise would be extremely high for small island nations. Indeed, as a percentage of GDP the Maldives, Kiribati, Tuvalu, Tokelau, Anguilla, Turks and Caicos, Marshall Islands and Seychelles were ranked among the ten nations with the highest protection costs in relation to GDP (Tsyban *et al*., 1990: 6. 4). Over twenty years later these two points continue to be emphasized. For instance, although small islands represent only a fraction of total global damage projected to occur due to a sea-level rise of 1.0 m by 2100 (SRES A1 scenario) the actual damage costs for the small island states is enormous in relation to the size of their economies (Anthoff *et al*., 2010: 328) with several small island nations (Nauru, Marshall Islands, Palau, Federated States of Micronesia) being included in the group of ten countries with the highest relative impact projected for 2100 (Anthoff *et al*., 2010: 328-330).

The Second Assessment (SAR) in 1995 confirmed the vulnerable state of small islands, now included in a specific chapter titled 'Coastal Zones and Small Islands' (Bijlsma, *et al*., 1996). However, importantly the SAR recognized that both vulnerability and impacts would be highly variable between small islands and that impacts were 'likely to be greatest where local environments are already under stress as a result of human activities' (Bijlsma, *et al*., 1996: 290-291). The report also summarized results from the application of a common methodology for vulnerability and adaptation analysis that gave new insights into the socio-economic implications of sea-level rise for small islands including: negative impacts on virtually all sectors including tourism, freshwater resources, fisheries and agriculture, human settlements, financial services and human health; protection is likely to be very costly; and, adaptation would involve a series of tradeoffs. It also noted that major constraints to adaptation on small islands included: lack of technology and human resource capacity, serious financial limitations, lack of cultural and social acceptability and uncertain political and legal frameworks. Integrated coastal and island management was seen as a way of overcoming some of these constraints.

The Third Assessment (TAR) in 2001 included a specific chapter on 'Small Island States'. In confirming previously identified concerns of small island states two factors were highlighted, the first relating to sustainability noting that 'with limited resources and low adaptive capacity, these islands face the considerable challenge of meeting the social and economic needs of their populations in a manner that is sustainable' (Nurse *et al*., 2001: 845). And the second, that there were other issues faced by small island states concluding that 'for most small islands the reality of climate change is just one of many serious challenges with which they are confronted' (Nurse *et al*., 2001: 846). Both of these themes are raised again and assessed in the light of recent findings in the present chapter.

Until the Fourth Assessment (AR4) in 2007, sea-level rise had dominated vulnerability and impact studies of small island states. Whilst a broader range of climate change drivers and geographical spread of islands was included in the 'Small Islands' chapter, Mimura *et al*. (2007) prefaced their assessment by noting that the number of 'independent scientific studies on climate change and small islands since the TAR' had been quite limited and in their view 'the volume of literature in refereed international journals relating to small islands and climate change since publication of the TAR is rather less than that between the SAR in 1995 and TAR in 2001' (Mimura *et al*., 2007: 690).

Since AR4 the literature on small islands and climate change has increased substantially. A number of features distinguish the literature we review here from that included in earlier assessments. First, the literature appears more sophisticated and does not shirk from dealing with the complexity of small island vulnerability, impacts and adaptation or the differences between island states. Second, and related to the first, the literature is less one-dimensional, and deals with climate change in a multidimensional manner as just one of several stressors on small island nations. Third, the literature also critiques some aspects of climate change policy, notably in relation to development and security of small islands, and suggests that adaptations for the future are being placed above

critical development needs of the present. As a result, it is argued, there is a reduction in resilience that will have serious ramifications for small island adaptation in the future.

29.3. Observed Impacts of Climate Change, including Detection and Attribution

The distinction between *observed* impacts of climate change and *projected* impacts is often unclear in the small islands literature and discussions. Publications frequently deal with both aspects of impacts interchangeably, and use observed impacts from, for instance an extreme seasonal event, as an analogy to what may happen in the future due to climate change (e.g. Lo-Yat *et al.,* 2011). The key climate and ocean drivers of change that impact small islands include variations in air and ocean temperatures, ocean chemistry, rainfall, wind strength and direction, sea-levels and wave climate and particularly the extremes such as tropical cyclones, drought and distant storm swell events. All have varying impacts, dependent on the magnitude and frequency and temporal and spatial extent, as well as on the bio-physical nature of the island and its social, economic and political setting.

[INSERT FIGURE 29-1 HERE
Figure 29-1: This schematic describes common tropical island typology from young high volcanic islands (left) through to atolls (submerged volcanics) on the far right. This simple overview highlights important components such as elevation and differing land and marine resources as well as the presence of coral reefs. On both high and low islands coastal settlement patterns predominate. Elevated limestone islands and islands comprised of 'continental' rocks are not included in this figure, but see Table 29-3.]

29.3.1. Observed Impacts on Island Coasts and Marine Biophysical Systems

29.3.1.1. Sea Level Rise, Inundation, and Shoreline Change on Small Islands

Sea-level rise poses one of the most widely recognized climate change threats to low-lying coastal areas (Church and White 2011; Cazenave and Llovel, 2010; Nicholls and Cazenave, 2010). This is particularly important in small islands where the majority of human communities and infrastructure are located in coastal zones with limited relocation opportunities especially on atoll islands (Woodroffe, 2008) (Figure 29-1). Rates of global average sea-level rise have continued at approximately 3.3 mm yr $^{-1}$ between 1993 and 2011 and acceleration is detected in longer records since 1870 (Merrifield *et al.,* 2009; Church and White, 2011) (See Chapter 13, Working Group 1). Rates of sea-level rise are however not uniform across the globe and large regional differences have been detected including in the south Indian Ocean and tropical Pacific, where rates have been significantly higher than the global average (Meyssignac *et al.,* 2012). In the tropical western Pacific where a large number of small island communities exist, rates up to four times the global average (approximately 12 mm yr $^{-1}$) have been reported between 1993 and 2009 and are generally thought to describe transient rates associated with natural cyclic climate phenomena such as ENSO (El Niño-Southern Oscillation) (Cazenave and Remy, 2011; Becker *et al*., 2012). Large interannual variability in sea level has also been demonstrated from the Indian Ocean (e.g Chagos Archipelago, Dunne *et.al.,* 2012) whilst in the Caribbean Palanisamy et al. (2012) found that over the last 60 years the mean rates of sea-level rise in the Caribbean region were similar to the global average ~ 1.8mm yr^{-1}.

There are few long-term sea level change trends for individual small island locations and the situation is hampered in many sites by the absence of adequate monitoring regimes. Furthermore, sea flooding and inundation is frequently associated with sea level extremes caused by transient phenomena, e.g.; surge, storm wave and routine lunar (tidal) cycles (Vassie *et al.,* 2004; Zahibo *et al*., 2007; Komar and Allan, 2008; Haigh *et al*., 2011). For example, high spring tide floods at Fongafale Island, Funafuti Atoll, Tuvalu, have been well publicized and study has shown that areas of the central portion of Fongafale are already below sea-level at high spring tide (Yamano *et al.,* 2007). Rates of relative sea level rise at Funafuti between 1950 – 2009 has been approximately three times higher than the global average (Becker *et al.,* 2012) and saline flooding of internal low-lying areas occurs regularly and is expected to become more frequent and extensive over time (Yamano *et al.,* 2007).

Documented cases of coastal inundation and erosion often cite extenuating circumstances such as vertical subsidence, engineering works, development activities or beach mining. Three examples can be cited. First, on the Torres Islands, Vanuatu communities have been displaced due to increasing inundation of low-lying settlement areas due to a combination of tectonic subsidence and sea-level rise (Ballu *et al.,* 2011). Second, on Anjouan Island, Comores in the Indian Ocean, Sinane et al. (2010) found beach aggregate mining was a major contributing factor influencing rapid beach erosion. Third, the intrinsic exposure of rapidly expanding settlements and agriculture in the low-lying flood prone Rewa Delta, Fiji is shown by Lata and Nunn (2012) to place populations in increasingly severe conditions of vulnerability to flooding and marine inundation.

Since the AR4 several studies have documented changes in island shorelines over the last few decades. Historical shoreline position change over 20 – 60 years on 27 central Pacific atoll islands showed that total land area remained relatively stable in 43 per cent of islands, whilst another 43 per cent had increased in area; and the rest showed a net reduction in land area (Webb and Kench, 2010). Dynamic responses were also found in a four year study of 17 relatively pristine islands on two other central Pacific atolls in Kiribati by Raney (2011) who concluded that sea-level rise was not likely to be the main influencing factor in these shoreline changes. On uninhabited Raine Island on the Great Barrier Reef, Dawson and Smithers (2010) also found that shoreline processes were dynamic but that island area and volume increased 6 per cent and 4 per cent, respectively between 1967 and 2007. Overall, these and other studies conclude that normal seasonal erosion and accretion processes appear to predominate over any long-term morphological trend or signal.

In many locations changing patterns of human settlement and direct impacts on shoreline processes present immediate erosion challenges in populated islands and coastal zones (Yamano *et al*., 2007; Storey and Hunter, 2010; Novelo-Casanova and Suarez, 2010) and mask attribution. A study of Majuro atoll (Marshall Islands) found that erosion was widespread but attribution to factors like sea level rise were masked by pervasive anthropogenic impacts to the coastal system (Ford, 2012). Similarly a study of three islands in the Rosario Archipelago (Colombia) reported shoreline retreat over a 50-55 year span and found Grande, Rosario, and Tesoro Islands had lost 6.7, 8.2 and 48.7 per cent of their land area respectively. Erosion was largely attributed to management issues on densely settled Grande Island, whilst sea level increase and persistent northeast winds enhanced erosion on uninhabited Rosario, and Tesoro (Restrepo *et al.,* 2012). Likewise, Cambers (2009) reported average beach erosion rates of 0.5 m yr^{-1} in eight Caribbean islands from 1985-2000 and whilst the study could not quantify the extent of attribution it did highlight that greater erosion rates were positively correlated with the number of hurricane events. Alternately, Etienne and Terry (2012) found the net shoreline impacts of a category 4 cyclone which passed within 30 km of Taveuni Island (Fiji) nourished shorelines with fresh coralline sediments despite localized storm damage. These studies contribute to improved understanding of island shoreline processes and change since AR4 though the vulnerability of small island shores and low-lying areas to increasing inundation and erosion in response to sea level rise and other potential climate change stressors provided in AR4, remains unchanged.

29.3.1.2. Coastal Ecosystem Change on Small Islands: Coral Reefs and Coastal Wetlands

Coral reefs are an important resource in small tropical islands and the culture and wellbeing of island communities is linked to their on-going function and productivity. They play a significant role in supplying sediment to island shores and in mediating wave energy this reducing potential at-shore erosion. They also provide habitat for a host of marine species upon which many island communities are dependent for subsistence diets as well as underpinning beach and reef-based touristic economic activity (Bell *et al.,* 2011; Perch-Nielsen, 2010). The documented sensitivity of coral reef ecosystems to climate change is summarized elsewhere (see Box CC-CR).

Increased coral bleaching due to thermal stress and reduced calcification rates due to increasing CO_2 concentration are expected to affect the function and viability of living reef systems (Hoegh-Guldberg *et al.,* 2007; Eakin *et al.,* 2009) and some studies are starting to observe impacts consistent with regional reef decline (De'ath *et al*., 2009; Tanzil *et al.,* 2009; Cantin *et al.,* 2010). Unprecedented bleaching events in small islands have been recorded iin the remote Phoenix Group (Kiribati) where there had been near 100 per cent coral mortality in the lagoon environment and 62 per cent mortality on the outer leeward slopes of the otherwise pristine reefs of Kanton Atoll during 2002 / 2003 (Alling *et al*., 2007). Similar patterns of mortality were observed in four other atolls in the Phoenix group and

temperature-induced coral bleaching was also recorded in isolated and unpopulated Palmyra Atoll during the 2009 ENSO event (Williams *et al*., 2010). In 2005 extensive bleaching was recorded at 22 sites around Rodrigues Island in the western Indian Ocean with up to 75% of the dominant species affected in some areas (Hardman *et al*., 2007). Studies of the severe 1998 El Niño bleaching event in the tropical Indian Ocean showed reefs in the Maldives, Seychelles and Chagos Islands were among the most impacted (Cinner *et al*., 2012; Tkachenko, 2012). In 2005 a reef survey around Barbados following a Caribbean regional bleaching event revealed the most severe bleaching ever recorded with approximately 70% of corals impacted (Oxenford *et al*., 2008). Globally, the incidence and implications of temperature-related coral bleaching in small islands is well documented and the synergistic effect of increasing ocean acidification can be considered a threat to the long-term persistence of island coral reef ecosystems (see Box CC-OA).

Island reefs have limited defences against thermal stress and acidification. However studies such as Cinner et al. (2012) and Tkachenko (2012) highlight that whilst recovery from bleaching is variable, some reefs show greater resilience that has important implications for reef protection and management regimes. Additionally, there is evidence that coral reef resilience is enhanced in the absence of other environmental stresses such as declining water quality. In Belize chronologies of growth rates in massive corals *Montastraea faveolata* over the past 75–150 years show that the bleaching event in 1998 was unprecedented but that the severity of the response also appeared to stem from reduced thermal tolerance resulting from the direct effect of human coastal development (Carilli *et al*., 2010). Likewise a study over a 40 year period (1960's – 2008) in the Grand Recif of Tulear, Madagascar concluded that severe degradation was mostly ascribed to direct anthropogenic disturbance of the near shore marine environment, despite an average 1^0C increase in temperature over this period (Harris *et al*., 2010). Coral recovery following the 2004 bleaching event in the central Pacific atolls Tarawa and Abaiang (Kiribati) was also noted to likely be improved in the absence of direct human impacts (Donner *et al*., 2010).

The loss of coral reef habitat has dire implications to coastal fisheries (Pratchett *et al*., 2009) in small islands where reef based subsistence and tourism activities are often critical to the wellbeing and economies of islands (Bell *et al*., 2011). In Kimbe Bay, Papua New Guinea 65% of coastal fish are dependent on living reefs at some stage in their life cycles and that there is a decline in fish abundance following reef degradation (Jones *et al*., 2004). Even where coral reef recovery occurs following bleaching, reef associated species composition may not recover to its original state (Pratchett *et al*., 2009; Donner *et al*., 2010). In reefs where bleaching has not been an immediate threat, SST anomaly events like that reported by Lo-Yat *et al*., (2011) between 1996 and 2000, showed an associated lag in larval supply of coral reef fishes of Rangiroa Atoll, French Polynesia. Higher temperatures have also been implicated in negative affects to spawning of adult reef species (Munday *et al*., 2009; Donelson *et al*., 2010).

Like coral reefs, mangroves and sea grass environments provide a range of ecosystem goods and services (Polidoro *et al*., 2010 and Waycott *et al*., 2009) and both habitats play a significant role in the wellbeing of small island communities. Mangroves in particular perform a host of commercial and subsistence uses as well as providing natural coastal protection from erosion and storm events (Ellison, 2009; Krauss *et al*., 2010; Waycott *et al*., 2011).

Sea-level rise is reported as the most significant climate change threat to the survival of mangroves (McKee *et al*., 2007; Waycott *et al*., 2011) and the loss of seaward edge of mangroves at Hungry Bay, Bermuda has been recorded by Ellison (1993) who attributes this to ongoing sea-level rise and the inability of mangroves to tolerate the increased inundation at the seaward margin. Elsewhere in the Caribbean and tropical Pacific observations vary in regards to the potential for sedimentation rates in mangroves forests to keep pace with sea-level rise (McKee *et al*., 2007; Krauss *et al*., 2003). In Kosrae and Pohnpei Islands (Federated States of Micronesia), Krauss *et al*., (2010) found significant variability in mangrove average soil elevation changes due to deposition from a deficit of 4.95 mm y^{-1} to a surplus of 3.28 mm y^{-1} relative to their sea-level rise estimates. This depositional potential is mostly reported from high island studies via the addition of terrigenous sediment inputs. However, Rankey's (2011) study of shoreline change in atolls in Kiribati also noted natural seaward migration (up to 40m) of some mangrove areas between 1969 and 2009 suggesting sediment accretion can also occur in the absence of terrigenous inputs. Otherwise, in the absence of vertical accretion landward migration may occur where accommodation space permits (Gilman *et al*., 2008) though in small islands accommodation space is seldom extensive as illustrated by Martinique in the Caribbean (Schleupner, 2008).

The response of sea grass to climate change stress is also likely to be complex, regionally variable and manifest in quite different ways. A study of seven species of sea grasses from tropical Green Island, Australia highlighted the variability in response to heat and light stress (Campbell *et al*., 2006). Light reduction may be a limiting factor to sea grass growth due to increased depth (Ralph *et al.,* 2007) and Ogston and Field (2010) observed that a 20 cm rise in sea level may double suspended sediment loads and turbidity in shallow waters on Hawaii's Molokai Island's fringing reefs, with negative implications to photosynthetic species such as seagrass. Otherwise, temperature stress is most commonly reported as the main expected climate change impact on sea grass (e.g. Marbá and Duarte 2010; Campbell *et al.,* 2006; Waycott *et al.,* 2011). Literature on seagrass diebacks in small islands is scarce but research in the Balearic Islands (Western Mediterranean) has shown that over a six-year study, sea grass shoot mortality and recruitment rates were negatively influenced by higher temperature (Marbá and Duarte, 2010).

29.3.2. Observed Impacts on Terrestrial Systems: Island Biodiversity and Water Resources

Climate change impacts on terrestrial biodiversity on islands, frequently interacting with several other drivers (Blackburn *et al*., 2004; Didham *et al*., 2005), fall into three general categories namely: (a) ecosystem and species horizontal shifts and range decline; (b) altitudinal species range shifts and decline mainly due to temperature increase on high islands; and (c) exotic and pest species range increase and invasions mainly due to temperature increase in high latitude islands. Due to the limited area and isolated nature of most islands, these effects are generally magnified compared to continental areas and may cause species loss especially in tropical islands high in endemics. For example, decline in the long-term persistence of freshwater-dependent ecosystems within two low-lying Caribbean carbonate islands in the Bahamas have been attributed to the synergistic impacts of increasing sea level and reduced rainfall. Greaver and Sternberg (2010) found that during periods of reduced rainfall the shallow freshwater lens subsides and contracts landward and ocean water infiltrates further inland below coastal strand vegetation. The combination of drier conditions and saline incursion in deeper soils negatively impacts vegetation formerly reliant on deeper freshwater reserves. Sea level rise has been observed to threaten the long-term persistence of freshwater-dependent ecosystems within low-lying islands in the Florida Keys in the northern end of the Caribbean (Goodman *et al*., 2012). On Sugarloaf Key, Ross et al. (2009) found pine forest area declined from 88 to 30 h from 1935 to 1991 due to increasing salinization and rising ground water, with vegetation transitioning to more saline tolerant species such as mangroves.

Whilst there are many studies that report observations associated with temperature increases in mid- and high-latitude islands, such as the Falkland Islands and Marion Islands in the south Atlantic and south Indian ocean respectively (Bokhorst *et al*., 2007; 2008; (Le Roux *et al*., 2005) and Svalbard in the Arctic (Webb *et al*., 1998) there are few equivalent studies in tropical small islands. One exception is a recent study of the tropical bird species the Mauritius kestrel that indicates changing rainfall conditions in the island of Mauritius over the last 50 years has resulted in this species having reduced reproductive success due to a mismatch between the timing of breeding and peak food abundance (Senapathi *et al*., 2011).

Increasing global temperatures also lead to altitudinal species range shifts and contractions within high islands with an upward creep of the tree line and associated faunal species (Benning *et al*., 2002). Comparative vegetation distribution and composition studies in sub-Antarctic Marion Island, found an altitudinal shift of 3.4 m per year for plant species (Parolo and Rossi 2008). Comparative effects also occur in the tropics such as the Hawaii Volcano National Park where comparison of sample plots over a 40 year period from 1966-67 to 2008 show climate change attributed adaptation of fire adapted grasses upward in elevation (Angelo and Daehler, 2012). Reduction in the numbers and sizes of endemic populations caused by such habitat constriction and changes in species composition in mountain systems may result in demise and possibly extinction of endemic species (Chen *et al*., 2009; Pauli *et al*., 2007; Sekercioglu *et al.,* 2008). Altitudinal temperature change has also been reported to influence the distribution for disease vectors such as mosquitoes potentially threatening biota unaccustomed to such vectors (Freed *et al*., 2005).

Freshwater supply in small island environments has always presented challenges and has been an issue raised in all previous IPCC reports. On high volcanic and granitic islands small and steep river catchments respond rapidly to rainfall events and watersheds generally have restricted storage capacity. On porous limestone and low atoll islands

surface runoff is minimal and water rapidly passes through the substrate into the ground water lens. Rainwater harvesting is also an important contribution to freshwater access and alternatives like desalination have mixed success in small island settings due to operational costs (White and Falkland, 2010).

Rapidly growing demand, land use change, urbanisation and tourism are already placing significant strain on the limited freshwater reserves in small island environments (Cashman *et al*., 2010; Emmanuel and Spence, 2009; White and Falkland, 2010). In the Caribbean where there is considerable variation in the types of freshwater supplies utilised concern over the status of freshwater availability has been expressed for at least the past 30 years (Cashman *et al*., 2010). There have also been economic and management failures in the water sector not only in the Caribbean (Mycoo, 2007) but also in small islands in the Indian (Payet and Agricole, 2006) and Pacific oceans (Moglia *et al*., 2008a; 2008b; White *et al*., 2007) .

These issues also occur on a background of decreasing rainfall and increasing temperature. Rainfall records averaged over the Caribbean region for 100 years (1900-2000) show a consistent 0.18 mm/year reduction in rainfall, a trend that is projected to continue (Jury and Winter, 2010), In contrast, analysis of rainfall data over the past 100years from the Seychelles has shown substantial variability related to ENSO though an increase in average rainfall from 1959 to 1997 and an increase in temperature of ~ 0.25 °C per decade has occurred (Payet and Agricole, 2006). Detection of long-term statistical change in precipitation is one prerequisite to understanding the impacts of climate change in small island hydrology and water resources.

Much recent literature has focussed on saline (sea-water) intrusion into fresh groundwater reserves on atoll islands which is frequently attributed to incremental sea-level rise though there is a paucity of empirical evidence to support this premise (e.g. Rozell and Wong, 2010). White and Falkland's (2010) review of existing small island studies indicates that a sea level increase of up to 1 m would have negligible salinity impacts on atoll island groundwater lenses so long as there is adequate vertical accommodation space, island shores remain intact, rainfall patterns do not change and direct human impacts are managed. However, wave overtopping and wash over can be expected to become more frequent with sea level rise and this has been shown to impact freshwater lenses dramatically. On Pukapuka Atoll, Cook Islands storm surge over-wash occurred in 2005 and caused the fresh water lenses to become immediately brackish and took some 11 months to recover to conductivity levels appropriate for human use (Terry and Falkland, 2010). The ability of freshwater lens' to float upwards within the matrix of the island in step with incremental sea level rise also means that in low-lying and central areas of many atolls the lens may pond at the surface. This phenomenon already occurs in very low-lying central areas of Fongafale Island, Tuvalu, and during extreme high 'king' tides large areas of the inner part of the island become inundated with brackish waters (Yamano *et al*., 2007; Locke, 2009).

29.3.3. Observed Impacts on Human Systems of Small Islands

29.3.3.1. Observed Impacts on Island Settlements and Tourism

Whilst traditional settlements on high islands were often located inland, the move to coastal locations was encouraged by colonial and religious authorities and more recently through the development of tourism. Now the majority of settlements, infrastructure and development is located on low-lands along the coastal fringe of small islands. In the case of atoll islands, all development and settlement is essentially coastal. It follows that populations, infrastructure, agricultural areas and fresh groundwater supplies are all vulnerable to extreme tides, wave and surge events and sea level rise (Walsh *et al*., 2012). Population drift from outer islands or from inland, together with rapid population growth in main centers and lack of accommodation space drives growing populations into ever more vulnerable locations. Additionally, without adequate resources and planning, engineering solutions such as shoreline reclamation also place communities and infrastructure in positions of increased risk (Schleupner, 2008; Yamano *et al*., 2007).

Many of the environmental issues that the media raise relating to Tuvalu, the Marshall Islands and Maldives are in fact only relevant to the major center and its surrounds, that is Funafuti, Majuro and Male respectively. As an example Storey and Hunter (2010) indicate the 'Kiribati' problem does not refer to the whole of Kiribati but rather

to the southern part of Tarawa atoll where preexisting issues of severe overcrowding, proliferation of informal housing and unplanned settlement, inadequate water supply, poor sanitation and solid waste disposal, pollution and conflict over land ownership are of concern. They argue that these problems require immediate resolution if the vulnerability of the South Tarawa community to the 'real and alarming threat' of climate change is to be managed effectively (Storey and Hunter, 2010).

On Majuro atoll, rapid urban development and the abandonment of traditional settlement patterns has resulted in movement from less vulnerable to more vulnerable locations on the island (Spennemann, 1996). Likewise, geophysical studes of Fongafale Island, the capital of Tuvalu, show that engineering works during World War II, and rapid development and population growth since independence, has lead to the settlement of inappropriate shoreline and swampland areas leaving communities in heightened conditions of vulnerability (e.g. Yamano *et al.*, 2007). Ascribing direct climate change impacts in such disturbed environments is problematic due to the existing multiple lines of stress on the island's biophysical and social systems. However, it is clear that such pre-existing conditions of vulnerability add to the threat of climate change in such locations.

The issue of 'coastal squeeze' remains a concern for many small islands as there is a constant struggle to manage the requirements for physical development against the need to maintain ecological balance (Fish *et al.,* 2008; Sano *et al.,* 2010; Gero *et al.*, 2011; Mycoo, 2011). Martinique in the Caribbean exemplifies the point, where physical infrastructure prevents the beach and wetlands from retreating landward as a spontaneous adaptation response to increased rates of coastal erosion (Schleupner, 2008). Moreover, intensive coastal development in the limited coastal zone combined with population growth and tourism have placed great stress on the coast and has resulted in dense aggregations of infrastructure and people in potentially vulnerable conditions.

Tourism is an important sector on many small islands. Linkages between weather, climate and tourism in small islands have been assessed on several occasions, including in IPCC assessments. There is currently no evidence that observed climatic changes in small island destinations or source markets have altered patterns of demand for tourism to small islands (Scott *et al.,* 2012a). There is also no systematic analysis of how recent extreme storm events have impacted tourism operations (costs of evacuations, damages, recovery interruption, insurance) in small islands (UNWTO, 2010).

Climate can also impact directly on environmental resources that are major tourism attractions in small islands. Beach erosion is widespread and has been found to negatively impact destination attractiveness and accommodation prices (Houston 2002, Cowell *et al.,* 2006, Buzinde *et al.,* 2010a, 2010b, Hamilton 2007). Erosion caused by Hurricane *Wilma* in 2005 at renowned coastal tourism destinations in Mexico is indicated of these impacts. Tourist perceptions of the beach erosion and restoration ranged from aesthetically unpleasant and feeling deceived by marketing of extensive beaches to focusing on new recreational opportunities provided by the erosion control structures in the water (Buzinde *et al.*, 2010a, 2010b). Visitation at Cancun declined roughly 50% in the year following the erosion, but as beach restoration continued, arrivals recovered to pre-erosion levels in 2007 (Scott *et al.,* 2012b). It is unclear whether the extent of this recovery would have occurred without the extensive investment in beach restoration.

Higher surface water temperatures continue to cause coral bleaching near many small islands. Severe bleaching caused several marine parks and dive sites in Southeast Asia and the Indian Ocean to close during 2010, in an attempt to try and reduce further damage (Sarnsamak, 2011). Studies reveal dive tourists are well aware of coral bleaching, particularly the experienced diver segment (Cesar, 2000; Westmacott *et al.,* 2000, Ngazy *et al.,* 2005, Gössling *et al.,* 2008, Kragt *et al.,* 2009, Klint *et al.,* 2012a, 2012b, Klinthong 2012), and therefore more acute impacts occur among tourism operators and resorts that cater to these markets. No information is available on how changes in marine ecology are influencing the sport fishing industry of small islands (Scott *et al.,* 2012b).
The availability of freshwater is limited on many small islands, and changes in the availability or quality during drought events linked to climate change have adverse impacts on tourism operations (Gössling *et al.,* 2012, UNWTO 2012). One aspect of this that cruise ships may cease coming to an island where there is not sufficient freshwater to restock their supplies. Tourism is a seasonally significant water user in many island destinations and in times of drought, concerns over limited supply for residents and other economic activities become heightened (Tapper *et al.,* 2011, Gössling *et al.,* 2012). As a consequence, some islands are investing in coral reef restoration,

beach rehabilitation, water demand management and desalination plants in attempts to reverse the negative publicity arising from those observed impacts. There is no analysis of how widespread these investments are or their capability to cope effectively with future climate change. The tourism industry and investors are also beginning to consider the climate risk of tourism operations (Scott *et al.,* 2012b).

29.3.3.2. Observed Impacts on Human Health of Island Populations

Globally, the effects of climate change on human health will be both direct and indirect, and are expected to exacerbate existing health risks, especially in the most vulnerable communities where the burden of disease is already high (refer to Chapter 11.3, 11.5 and 11.6.1, this volume).Many small island states currently suffer from climate-sensitive health outcomes, including morbidity and mortality from extreme weather events, certain vector- and food- and water-borne diseases (Barnett and Campbell, 2010; Cashman *et al.,*2010; Pulwarty *et al.,* 2010; McMichael and Lindgren, 2011). Extreme weather and climate events such as tropical cyclones, storm surges, flooding, and drought can have both short-and long-term effects on human health, including drowning, injuries, increased disease transmission, and health problems associated with deterioration of water quality and quantity. Most small island nations are in tropical areas with weather conducive to the transmission of diseases such as malaria, dengue, filariasis, and schistosomiasis.

The linkages between human health, climate variability and seasonal weather have been demonstrated in several recent studies. The Caribbean has been identified as a 'highly endemic zone for leptospirosis' with Guadeloupe, Barbados, and Jamaica representing the highest annual incidence (13 to 7.8 per 100,000 population) in the world with only the Seychelles being higher (43.2 per 100,000 population) (Pappas *et al.,* 2008). Studies conducted in Guadeloupe demonstrated a link between El Niño occurrence and leptospirosis incidence with rates increasing to 13 per 100,00 population in El Nino years as opposed to 4.5 cases per 100,00 inhabitants in La Niña and neutral years (Herrmann-Stock *et al.,* 2008). In addition, epidemiological studies conducted in Trinidad reviewed the incidence of leptospirosis during the period 1996-2007 and showed seasonal patterns in the occurrence of confirmed leptospirosis cases, with significantly ($P<0.001$) more cases or 75% of all cases occurring in the wet season, May to November (193 cases), than during the dry season, December to May (66 cases) (Mohan *et al*., 2009). Recently changes in the epidemiology of leptospirosis have been detected especially in tropical islands with the main factors being climatic and anthropogenic (Pappas *et al*., 2008) that are likely to be enhanced with increases in ambient temperature and changes in precipitation, vegetation and water availability as a consequence of climate change (Russell, 2009).

In Pacific islands the incidence of diseases such as malaria and dengue fever has been increasing, especially endemic dengue in Samoa, Tonga and Kiribati (Russell, 2009). While studies conducted so far in the Pacific have only established a direct link between malaria, dengue and climate variability, these and other health risks including from cholera, are projected to increase as a consequence of climate change (Russell, 2009; refer also to Chapter 11.2.4 and 11.2.5 this volume, for detailed discussion on the link between climate change and projected increases in the outbreak of dengue and cholera). Dengue incidence is also a major health concern in other small island countries, including Trinidad and Tobago, Singapore, Cape Verde, Comoros and Mauritius (Chadee *et al*, 2007; Chadee 2009; Koh *et al.,* 2008; Van Kleef *et al.,* 2010; Teles, 2011). In the specific cases of Trinidad and Tobago, the outbreaks have been significantly correlated with rainfall and temperature, respectively (Chadee *et al.,* 2007; Chadee 2009; Koh *et al.,* 2008).

Previous IPCC assessments have consistently shown that human health on islands can be seriously compromised by lack of access to adequate, safe, fresh water and adequate nutrition (Nurse *et al*., 2001; Mimura *et al*., 2007). Lovell (2011) notes that in the Pacific many of the anticipated health effects of climate change are expected to be indirect, connected to the increased stress and declining well-being that comes with property damage, loss of economic livelihood and threatened communities. There is also a growing concern in island communities in the Caribbean, Pacific and Indian Ocean, that fresh water scarcity, more intense droughts and storms could lead to a deterioration in standards of sanitation and hygiene (Cashman *et al*., 2010; McMichael and Lindgren, 2011). In such circumstances, increased exposure to a range of health risks including communicable diseases would be a distinct possibility.

Ciguatera fish poisoning (CFP) occurs in tropical regions and is the most common non-bacterial food-borne illness associated with consumption of fish. Distribution and abundance of the organisms that produce these toxins, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with water temperature. Consequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of CFP in the island regions of the Caribbean (Morrison *et al.,* 2008; Tester *et al.,* 2010), Pacific (Llewellyn, 2010; Rongo and van Woesik, 2011; Chan et al, 2011) and the Mediterranean *(Aligizaki and Nikolaidis, 2008; refer also to section 29.5.4)*. One of the objectives of the Caribbean study was to characterize the relationships between sea surface temperatures (SSTs) and CFP incidence rates. This was done in tandem with a series of experiments designed to determine the effects of temperature on the growth rate of organisms responsible for CFP. High rates in the Lesser Antilles occur in areas which experience the warmest water temperatures and which show the least temperature variability. There are also high rates in the Pacific in Tokelau, Tuvalu, Kiribati, Cook Islands and Vanuatu.

The influence of climatic factors on malaria vector density and parasite development is well established (Beguin *et al.,* 2011; Chaves and Koenraadt, 2010). Previous studies have assessed the potential influence of climate change on malaria, using deterministic or statistical models (Hay *et al.,* 2009; Martens *et al*., 1999; Parham and Michael, 2010; Pascual *et al*., 2006). While the present incidence of malaria on small islands is not reported to be high, favourable environmental and social circumstances for the spread of the disease are present in some island regions, and are expected to be enhanced under projected changes in climate in Papua New Guinea, Guyana, Suriname and French Guyana **(**Michon *et al.,* 2007**;** Rawlins *et al.,* 2008; Figueroa, 2008), In the Caribbean, the occurrence of autochthonous malaria in non-endemic island countries in the last ten years, suggests that all of the essential malaria transmission conditions now exist, and Rawlins et al. (2008) call for enhanced surveillance, recognizing the possible impact of climate change on the spread of anopheles and malaria transmission.

29.3.3.3. Observed Impacts of Climate Change on Relocation and Migration

Empirical evidence of human migration as a response to climate change is scarce for small islands – in terms of a lack of studies showing the direct impacts of climate change on human settlements, and how these impacts lead to changes in migration and resettlement attitudes and behaviours. Several authors highlight this lack of empirical studies of the effect of climate drivers such as sea level rise, on island migration (Lilleor and Van den Broeck, 2011: s78, Mortreux and Barnett, 2009). Further there is no evidence of any government policy that allows for climate 'refugees' from islands to be accepted into another country (Bedford and Bedford, 2010). This surprising finding contrasts with the early desk-based estimates of migration under climate change such as the work of Myers (2002). These early studies have been criticised as they fail to acknowledge: the reality of climate impacts on islands, the capacity of islands and islanders to adapt, or the actual drivers of migration (Barnett and O'Neill, 2012).

The majority of studies on island migration reveal that the key drivers are economic or cultural and not climatic. For example when looking at historical process of migration within the Mediterranean it appears that rising levels of income, coupled with a decreased dependence on subsistence agriculture has left the Mediterranean less vulnerable to all environmental stressors, resulting in a reduced need for mobility to cope with environmental or climatic change (de Haas, 2011). Studies from the Pacific have also shown that culture, lifestyle and a connection to place are more significant drivers of migration than climate (Mortreux and Barnett, 2009, Barnett and Webber, 2010). For example a Pacific Access Category of migration has been agreed between New Zealand and Tuvalu that permits 75 Tuvaluans to migrate to New Zealand every year (Kravchenko, 2008). Instead of enabling climate driven migration, this agreement is designed to facilitate economic and social migration as part of the Pacific island lifestyle (Shen and Gemenne, 2011). Thus, there is no evidence *yet* that reveals that migration from islands is being driven by climate change.

Nonetheless there is recognition that environmental change affects land use and land rights, which in turn are drivers of migration (Bedford and Bedford, 2010). In a survey of 86 case studies of community relocations in Pacific islands, Campbell et al. (2005) found that environmental variability and natural hazards accounted for 37 communities relocating. In the Pacific, where land rights are a source of conflict, climate change could increase levels of stress associated with land rights, and impact on migration (Campbell, 2010; Weir and Virani, 2011).

While there is not yet a climate fingerprint on migration and resettlement patterns in small islands, it is clear that there is the potential for human movement as a response to climate change. To better understand the impact of climate change on migration there is an urgent need for robust methods to identify and measure the effects of the drivers of migration on migration and resettlement.

29.3.3.4. Observed Impacts on Island Economies

The economic and environmental vulnerabilities of small islands states are well documented (Briguglio *et al.,* 2009, Bishop, 2012). Such vulnerabilities, which render the states at risk of being harmed by economic and environmental conditions, stem from intrinsic features of these states, and are not governance induced (although poor governance in this regard may aggravate the harm).

Economic vulnerability is the result of a high degree of exposure to economic conditions often outside the control of small island states, exacerbated by dependence on a narrow range of exports and a high degree of dependence on strategic imports, such as food and fuel (Briguglio *et al.,* 2009). This leads to economic volatility, a condition that is harmful for the economy of the islands (Guillaumont, 2010).

There are other economic downsides associated with small size and insularity. Small size leads to high overhead cost per capita, particularly in infrastructural outlays. This is of major relevance to climate change adaptation as this often requires upgrades and redesign of island infrastructure. Insularity leads to high cost of transport per unit, associated with purchases of raw materials and industrial supplies in small quantities, as well as high cost of storing and warehousing to ensure adequate supply of production inputs and consumer goods. These disadvantages are associated with the inability of small islands to reap the benefits of economies of scale resulting in a high cost of doing business in small islands (Winters and Martins, 2004).

The environmental vulnerability of small island states stems from various intrinsic features, including the high ratio of coastline to land mass, rendering these states highly exposed to ocean borne hazards and to sea-level rise (Barnett and Campbell, 2010, Nicholls and Cazenave, 2010). Small island states are also highly prone to natural disasters (Peduzzi *et al.,* 2009; Turvey, 2007). Other environmental problems associated with small territory size relate to the high population densities of many small island states, which leads to a high per capita cost of waste management, traffic congestion, relatively high degree of biodiversity loss, heavy strain on water resources and other environmental harm associated with population pressure.

These economic and environmental problems are exacerbated by climate change, particularly because government funds have to be diverted from the normal budget outlays to cover additional expenditures associated with mitigation and adaptation to climate change. In addition, a large proportion of economic activity of many small island states, particularly those associated with tourism and fisheries, are located right on the coastline and these are likely to be affected by sea-level rise and extreme weather events.

29.3.4. Detection and Attribution of Observed Impacts of Climate Change on Small Islands

While exceptional vulnerability of many small islands to future climate change is widely accepted, the foregoing analysis indicates that scientific literature on observed impacts is quite limited. Detection of past and recent climate change impacts is challenging due to the presence of other anthropogenic drivers, especially in the constrained environments of small islands. Attribution is further challenged by the strong influence of natural climate variability compared to incremental change of climate drivers. Notwithstanding these limitations we have prepared a summary of the relationship between detection and attribution to climate change of several of the phenomena described in the above sections. Figure 29-2 reflects our degree of confidence in the linkage between observed changes in several components of the coastal, terrestrial and human systems of small islands and the drivers of climate change.

[INSERT FIGURE 29-2 HERE
Figure 29-2: Based on available literature discussed in this chapter, the diagram shows a comparison of the degree of confidence in the detection of tropical small island impacts (horizontal axis) with the degree of confidence in attribution to climate change drivers (vertical axis). For example; the blue symbol No. 2 (Coastal Systems), indicates there is very high confidence in both the detection of "sea-level rise consistent with global means" and its attribution to climate change drivers; whereas the yellow symbol No. 17 (Human Systems) indicates whilst detection of "casualties and damage during extreme events" is very high, at this time there is low confidence in the attribution to climate change drivers. It is important to note that low confidence in attribution frequently arises due to the very limited research available for small island environments.]

29.4. Projected Integrated Climate Change Impacts

Small islands face many challenges in using climate change projections for policy development and decision-making. Primary among these is the absence of credible regional socio-economic scenarios relevant at the scale at which most decisions are taken. Scenarios are an important tool to help decision makers disaggregate vulnerability to the direct physical impacts of the climate signal from the vulnerability associated with socio-economic conditions and governance. Before building socio-economic scenarios to aid decision making, there has to be scientifically credible simulation of future small island climates. In this regard, there is a serious problem in generating climate scenarios at the scale of small islands since they are generally much smaller than the resolution of the global models. This is because the grid squares in the Global Circulation Models (GCMs) used in the SRES scenarios over the last decade, were between 200 and 600 km^2, which provides inadequate resolution over the land areas of virtually all small islands.

The scale problem has been usually addressed by the implementation of statistical downscaling models that relate GCM output to the historical climate of a local small island data point. The limitation of this approach is the need for observed data ideally for at least three decades for a number of representative points on the island, in order to establish the statistical relationships between GCM data and observations. In most small islands long-term quality-controlled climate data is generally sparse, so that in widely dispersed islands such as in the Pacific, observational records are usually supplemented with satellite observations combined with computer models (Australian Bureau of Meteorology and CSIRO, 2011a; Keener *et al*., 2012). However where adequate local data is available for several stations for at least 30 years, downscaling techniques have demonstrated that they can respond to the guidance of the GCMs to closely match the local domain and that they require less computational demand (e.g. Charlery and Nurse, 2010). Even so, most projected changes in climate for the Caribbean, Pacific, Indian Ocean and Mediterranean islands, generally apply to the region as a whole and this may f be adequate to determine general trends in regions where islands are close together.

29.4.1. Non-Formal Scenario-Based Projected Impacts

Scenarios are often constructed by using a qualitative climate projections approach based on expected changes in some physical climate signal from literature review rather than direct modelling. Sometimes this is proposed as a 'what if' question which is then quantified using a numerical method. For example, in the Caribbean, sea level projections superimposed on topographic maps have been used to estimate that 49-60% of resort properties would be damaged with a one metre sea-level rise, potentially transforming the competitive position and sustainability of coastal tourism destinations in the region (Scott *et al.,* 2012c). Another example of qualitative modelling from the Pacific is a case study from Nauru which uses local data and knowledge of climate to assess the GCM projections. It suggests that Nauru should plan for continued ENSO variability in the future with dry years during La Niña and an overall increase in mean rainfall and extreme rainfall events. Climate adaptation concerns which arise include water security and potential changes in extreme wet events which affect infrastructure and human health (Brown *et al., submitted*).

29.4.2. Projected Impacts for Islands based on Existing SRES Scenarios

Another approach to scenario development is to use the SRES projections more directly. The broad synthesis in the AR4 of climate scenario projections and impacts on small island regions (e.g. Mimura *et al.*, 2007) remains valid (see new RCP Projections in Figure 29-3). For example, Table 29-1 shows that in general for the SRES A1B more balanced medium emissions scenario, the projections suggest about a 2°C increase in temperature in the Caribbean, Indian Ocean and Pacific Ocean small islands regions by 2100 with an overall annual decrease in precipitation of about 12% in the Caribbean (see also AR5 WG 1, 14.7.4) and a 3-5% increase in the Indian and Pacific Oceans small island regions. There are important spatial differences however as for example among the more dispersed Pacific islands where the more equatorial regions are likely to get wetter and the sub-tropical high pressure belts drier as reported by AR5 WG I, however, in regions directly affected by the SPCZ and western portion of the ITCZ, the rainfall outlook is uncertain (AR5 WG 1, 14.7.13). The Mediterranean islands also have differences from the tropical small island pattern. Throughout the Mediterranean region, the length, frequency, and/or intensity of warm spells or heat waves are very likely to increase to the year 2100 (AR5 WG 1, 14.7.6).

[INSERT TABLE 29-1 HERE
Table 29-1: Small islands regions temperature and precipitation change projections for the SRES A1B scenario over the period 2080-2099 compared to 1980-1999. The table shows the minimum, median (50%), and maximum values of the mean temperature and precipitation responses from each of the 21 AR4 global models (adapted from WGI AR4 Table 11.1).

In the main regions in which most tropical or sub-tropical small island states are located, there are few independent peer reviewed scientific publications providing downscaled climate data projections, and virtually none illustrating the experience gained from their use for policy making. A projected 2ºC temperature increase by the year 2100 has potential far reaching consequences for sentinel ecosystems such as coral reefs that are important to tropical islands (see Chapter *6.2.2.4.4.*). This is because 'Degree Heating Months' (DHM) >2 ºC-month are the determined threshold for severe coral bleaching (Donner, 2009). For example Donner (2009) in a study of sea surface temperature (SST) across all coral reef regions using GCM ensemble projections forced with five different SRES future emissions scenarios, concluded that even warming in the future from the current accumulation of greenhouse gases in the atmosphere could cause over half of the world's coral reefs to experience harmfully frequent thermal stress by 2080. Further, this timeline could be brought forward to as early as 2030 under the A1B medium emissions scenario. He further states that thermal adaptation of 1.5 ºC would only delay the thermal stress forecast by 50–80 years. Donner (2009) also estimated the year of likelihood of a severe mass coral bleaching event due more than once every 5 years, to be 2074 in the Caribbean, 2074 in the western Indian Ocean, 2082 in the central Indian Ocean, 2065 in Micronesia, 2057 in the central Pacific, 2094 in Polynesia and 2073 in the eastern Pacific small islands regions.

Small island economies can also be objectively shown to be at greater risk from sea-level rise in comparison to other geographic areas. Such a study is the use of the FUND model to assess the economic impact of substantial sea-level rise in a range of socio-economic scenarios downscaled to the national level, including the four SRES storylines (Anthoff *et al.,* 2010). Although this study shows that in magnitude, a few regions experience most of the costs of sea-level rise by 2100, especially East Asia, North America, Europe and South Asia, these same results when expressed as percent of GDP show that most of the top ten and four of the top five most impacted are small islands from the Pacific (Micronesia, Palau, Marshall islands, Nauru) and Caribbean (Bahamas) (Anthoff *et al.,* 2010). The point is made that the damage costs for these small island states are enormous in relation to the size of their economies (Nicholls and Tol, 2006) and that together with deltaic areas they will find it most difficult to locally raise the finances necessary to implement protection (Anthoff *et al.*, 2010).

In the Caribbean, downscaled climate projections have been generated for some Caribbean islands using the Hadley Centre PRECIS regional model (Taylor *et al.*, 2007, Stephenson *et al.,* 2008). For the SRES A2 and B2 scenarios the PRECIS regional climate model projects an increase in temperature across the Caribbean of 1–4 °C with increasing rainfall during the latter part of the wet season from November–January, in the northern Caribbean (i.e. north of 22°N) and drier conditions in the southern Caribbean with a strong tendency to drying in the traditional wet season from June–October (Whyte *et al.*, 2008, Campbell *et al.,* 2011, Taylor *et al.,* 2013). Projected lengthening

seasonal dry periods, and increasing frequency of drought periods are expected to increase demand for water throughout the region under the SRES A1B scenario (Cashman *et al*., 2010). Decrease in crop yield is also projected in Puerto Rico for the SRES B1 (low), A2 (mid-high) and A1F1 scenarios during September although increased crop yield is suggested during February (Harmsen *et al*., 2009). Using a tourism demand model linked to the SRES A1F1 A2 B1 and B2 scenarios, the projected climate change heating and drying impacts are also linked to potential aesthetic, physical and thermal effects that are estimated to cause a change in total regional tourist expenditure of about +321, +356, -118 and -146 million US dollars from the least to the most severe emissions scenario respectively (Moore, 2010).

In the Indian Ocean, representative downscaled projections have been generated for Australia's two Indian Ocean territories the Cocos (Keeling) Islands and Christmas Island using the CSIRO Mark 3.0 climate model with the SRES A2 high emissions scenario (Maunsell Australia Pty Ltd., 2009). Future climate change projections for the two islands for 2070 include a 1.8°C increase in air temperature by 2070, probable drier dry seasons and wet seasons, a 40 cm rise in sea level and a decrease in intense tropical cyclones.

In the western tropical Pacific, extensive climate projections have been made for 15 small islands based on downscaling from an ensemble of 15 GCMs (Australian Bureau of Meteorology and CSIRO, 2011b). The temperature projections in this region dominated by oceans seem less than those seen globally ranging from +1.5 to 2.0 °C for the B1 low emissions scenario to +2.5 to 3.0 °C for the A2 high emissions scenario by the year 2090 relative to a 20 year period centred on 1990. Notably there is a expected trend of increasing rainfall as indicated by a projected increase in 20 year extreme rainfall events to an average of seven times per year, by 2090 under the A2 (high emissions) scenario (Australian Bureau of Meteorology and CSIRO, 2011b). In the tropical Pacific Ocean, another comprehensive assessment of the vulnerability of the fisheries and aquaculture sectors to climate change in 22 Pacific island countries and territories focussed on two future time-frames (2030 and 2100) and two SRES emissions scenarios, B1 (low emissions) and A2 (high emissions) (Bell *et al*., 2011). The results are not very different from the IPCC AR4 projections with projected temperature increases of about +1.0 to 1.5 ºC by 2100 and an increase in rainfall of 10-20% in equatorial regions. Estimates of the resulting projected changes in habitat area (mangroves, seagrasses, freshwater fish) coral reef cover, demersal fish production, skipjack and bigeye tuna for the two SRES scenarios are given in Table 29-2.

[INSERT TABLE 29-2 HERE
Table 29-2: Preliminary projected percentage changes in tuna catches relative to the 20 year average (1980-2000) and estimated percentage change to government revenue resulting from projected changes in the catch of skipjack tuna in 2030 and 2100 (Bell et al, 2011).]

Most anticipated changes in habitat and resource availability such as the commercial tuna catch are negative, with implications for government revenue and island food security (Bell *et al*., 2011, Bell *et al*., 2013).

In the Mediterranean islands of Mallorca, Corsica, Sardinia, Crete and Lesvos, Gritti et al. (2006) simulated the terrestrial vegetation biogeography and distribution dynamics under the SRES A1F1 and B1 scenarios. The simulations indicate that the effects of climate change are expected to be negligible within most ecosystems except for mountainous areas that are projected to be eventually occupied by exotic vegetation types from warmer, drier conditions. Cruz et al. (2009) report similar results for the terrestrial ecosystems of Madeira Island in the Mediterranean. Downscaled SRES A2 and B2 scenarios for the periods 2040 – 2069 and 2070 – 2099 suggest that the higher altitude native humid forest called the Laurissilva, may expand upwards in altitude, which could lead to a severe reduction of the heath woodland which because it has little upward area to shift may reduce in range or disappear at high altitudes resulting in the loss of rare and endemic species within this ecosystem.

29.4.3. RCP Projections and Implications for Small Islands

Utilizing updated historical greenhouse gas emissions data the scientific community has produced future projections for four plausible new global Representative Concentration Pathways (RCPs) in order to explore a range of global climate signals up to the year 2100 and beyond (e.g. Moss *et al.,* 2010; van Vuuren *et al*., 2010). The RCPs are

named according to their global warming potential (e.g. RCP 4.5 W/m^2) and in an ongoing process are matched to a global socio-economic scenario storyline (SSP) such that each RCP can respond to more than one SSP. Scientists have strongly cautioned against the specification of detailed sub-global conditions and local trends based on these coarser global datasets and models. With these caveats in mind, typical representations of RCP projections for temperature and precipitation for similar times of the year in some small island regions are presented in Figure 29-3 adapted from Annex I WGI AR5. Highlighted in Figure 29-3 is the output of one model that is the mid-projection representation of each RCP model ensemble. A more comprehensive compilation of global RCP projections can be found in Annex I of the WGI AR5 Report.

[INSERT FIGURE 29-3 HERE
Figure 29-3: RCP Scenario projections to the year 2100 for the four main small island regions (adapted from AR5 WG1, Annex 1).]

Small Island Developing States (SIDS) advocated that the Global Mean Surface Temperature (GMST) increase should be limited to 'well below' 1.5ºC above pre-industrial levels (Hare *et al.,* 2011; Riedy and McGregor, 2011). Inspection of column 1 in Figure 29-3 suggests that for Caribbean, Indian Ocean and Pacific SIDS in the tropics, that is only plausible under RCP 2.6 that in each case yields about a 1ºC regional increase by 2100. RCP 2.6 also suggests no significant change in mean rainfall in the Caribbean with a slight increase for Indian and Pacific Ocean SIDS. In the mid-latitude Mediterranean Sea region RCP 2.6 yields about a 2ºC increase in temperature by 2100 and no apparent change in rainfall.

By comparison with regard to temperature, RCP 4.5 in Figure 29-3 suggest a probable less than 2ºC but not less than 1.5ºC temperature increase in Caribbean, Indian Ocean and Pacific SIDS by 2100 and about a 3ºC increase in the Mediterranean. Associated with this, the Caribbean and Mediterranean regions may experience a decrease in mean rainfall while the Indian and Pacific Ocean SIDS may experience increased rainfall. These trends accelerate moderately for RCP 6.0 and steeply for RCP 8.5.

29.5. Inter- and Intra-Regional Trans-Boundary Impacts on Small Islands

Many impacts on small islands are generated by processes originating in another region or continent well beyond the borders of an individual archipelagic nation or small island. These are inter-regional trans-boundary impacts. Intra-regional trans-boundary impacts originate from a within-region source (e.g. within the Caribbean). Some trans-boundary processes may have positive effects on the receiving small island or nation, though most that are reported have negative impacts. Deciphering a climate change signal in inter- and intra-regional trans-boundary impacts on small islands is not easy and usually involves a chain of linkages tracing back from island-impact to a distant climate or climate-related bio-physical or human process. Some examples are given below.

29.5.1. Large Ocean Waves from Distant Sources

Unusually large deep ocean swells, generated from far distant sources in the mid- and high-latitudes by Extra-Tropical Cyclones (ETC) cause considerable damage on the coasts of small islands thousands of kilometers away in the tropics. Impacts include sea-flooding and inundation of settlements, infrastructure and tourism facilities as well as severe erosion of beaches. Examples from small islands in the Pacific and Caribbean are common though perhaps the most significant instance, in terms of a harbinger of climate change and sea-level rise, occurred in the Maldives in April 1987 when long period swells originating from the Southern Ocean some 6000 km away caused major flooding, damage to property, destruction of sea defences and erosion of reclaimed land and islands (Harangozo, 1992). The Maldives and several other island groups in the Indian Ocean have been subject to similar ocean swell events more recently, most notably in May 2007 (Department of Meteorology, 2007).

In the Caribbean northerly swells affecting the coasts of islands have been recognized as a significant coastal hazard ever since the 1950s (Donn and McGuinness, 1959). They cause considerable seasonal damage to beaches, marine ecosystems and coastal infrastructure throughout the Caribbean (Cambers, 2009; Bush *et al.*, 2009). These high-

energy events manifest themselves as long period, high-amplitude waves generated by extra-tropical cyclones and high latitude lows originating thousands of kilometers away in the North Atlantic. They occur during the northern hemisphere winter and often impact the normally sheltered, low-energy leeward coasts of the islands (Bush *et al.,* 2009; Cambers, 2009). Such swells have even reached the shores of Guyana on the South American mainland as illustrated by a swell event in October 2005 that caused widespread flooding and overtopping and destruction of sea defences (van Ledden *et al*., 2009).

Distant origin swells differ from the 'normal' wave climate conditions experienced in the Caribbean, particularly with respect to direction of wave approach, wave height and periodicity. Based on statistical analysis of wave data from voluntary observer ships (VOS), Gulev and Grigorieva (2006) suggest that significant wave heights have increased by between 10 – 40 cm/decade in both the North Atlantic and North Pacific, during the period 1958-2002. While significant wave height has been observed to increase in some regions, current model simulations project enhanced wave heights only in the Southern Ocean and the tropical South Pacific, and decreases in all other ocean basins (See AR5-WG1, 13.7.3.2). This may however be related to the challenge of downscaling 'future wind states from coarse resolution climate models into regional and global wave model projections' (AR5-WG1, 13.7.3).

Swell events of similar origin and characteristics also occur in the Pacific the best documented being in the Hawaiian island where there is evidence of damage to coral growth by swell from the north Pacific, especially during years with a strong El Nino signal (Fletcher *et al*., 2008). Hoeke et al. (submitted) describe inundation from mid-high latitude north and south Pacific waves respectively at Majuro (Marshall Islands) in November and December 1979 and along the Coral Coast (Fiji) in May 2011. They also describe in detail an inundation event in December 2008 that was widespread throughout the western and central Pacific and resulted in waves surging across low-lying islands causing severe damage to housing and infrastructure and key natural resources that affected about 100,00 people across the region. The proximate cause of this event was swell generated in mid-latitudes of the north Pacific Ocean, more than 4000 km from the furthest affected island (Hoeke *et al.,* submitted).

Whereas the origin of the long period ocean swells that impact small islands in the tropical regions come from the mid-and high-latitudes in the Pacific, Indian and Atlantic oceans, there are also instances of unusually large waves generated from tropical cyclones that spread into the mid- and high- latitudes. One example occurred during 1999 when tide gauges at Ascension and St. Helena Islands in the central south Atlantic recorded unusually large deep-ocean swell generated from distant Hurricane Irene (Vassie *et al*., (2004). The impacts of increasing incidence or severity of storms or cyclones is generally considered from the perspective of direct landfall of such systems, whereas all of these instances serve to show 'the potential importance of swells to communities on distant, low-lying coasts, particularly if the climatology of swells is modified under future climate change' (Vassie *et al*., 2004: 1095). From the perspective of those islands that suffer damage from this coastal hazard on an annual basis, this is an area that warrants further investigation.

Deep ocean swell waves and elevated sea-levels resulting from ETCs are examples of *inter-regional* trans-boundary processes; locally generated Tropical Cyclones (TCs) provide examples of *intra-regional* trans-boundary processes. Whilst hurricane force winds, heavy rainfall and turbulent seas associated with TCs can cause massive damage to both land and coastal systems in tropical small islands, the impacts of sea waves and inundation associated with far distant ETCs are limited to the coastal margins. Nevertheless both storm types result in a range of impacts covering island morphology, natural and ecological systems, island economies, settlements and human well-being (see Figure 29-4).

[INSERT FIGURE 29-4 HERE
Figure 29-4: Tropical and extra-tropical cyclone impacts on the coasts of small islands: a. Example of tropical cyclone impacts on small island coasts with reference; b. Example of extra-tropical cyclone (mid-high-latitude lows) impacts on small island coasts with reference.

1a. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 1b. Maldives, April 1987 (Harangozo, 1992); 2a.Taveuni (Fiji) March 2010 (Etienne and Terry, 2012); 2b. Funafuti atoll, Tuvalu, October 1972 (Baines *et al*.,1974); 3a. Society and Autrales Islands, French Polynesia, February 2010 (Etienne, 2012); 3b.Maldives, April 1987 (Harangozo, 1992); 4a. Viti Levu, Fiji, March 1997 (Terry, *et al.,* 2002); 5a.Society Islands, French Polynesia, February 2010 (Etienne, 2012); 6a. Curacao, Bonaire, Netherlands Antilles, November 1999 (Scheffers and

Scheffers, 2006); Hawaiian Islands (Fletcher *et al*.,, 2008); 8a. Marshall Islands, June 1905 (Spennemann, 1996); 9a. Pukapuka atoll, Cook Islands 2005 (Terry and Falkland, 2010); 9b. Solomon Islands, December 2008 (Hoeke, submitted); 10a. Vanuatu 2004 (Richmond and Savacool, 2012); 10b. Chuck, Pohnpei, Kosrae, Federated States of Micronesia, December 2008 (Hoeke, submitted); 11a. 12a. 13a. Tuamotu Islands, French Polynesia, 1982-83 (Dupon, 1987); 15a. Tubuai (Australes Islands) February 2010 (Etienne, 2012); 15b. Majuro, Marshall Islands, November 1979 (Hoeke, submitted); 16a. Vanuata February 2004 (Richmond and Savacool, 2012);16b. Coral Coast, Viti Levu, Fiji, May 2011 (Hoeke, submitted); 17a. Bora Bora,Raiatea, Maupiti, Tahaa, Hahine (Society Islands) February 2010 (Etienne, 2012);17b. Majuro, Kwajalein, Arno Marshall Islands,December 2008 (Hoeke, submitted); 18a. Vanuatu, February 2004 (Richmond and Savacool, 2012); 18b. Bismark Archiplago, Papua New Guinea, December 2008 (Hoeke, submitted); 19a. Tuamotu (French Polynesia) 1982-83 (Dupon, 1987).]

29.5.2. Trans-Continental Dust Clouds and their Impact

The transport of airborne Saharan dust across the Atlantic and into the Caribbean has engaged the attention of researchers for some time. The resulting dust clouds are known to carry pollen, microbes, insects, bacteria, fungal spores and various chemicals (Prospero *et al*., 2005; Middleton *et al*., 2008; Monteil, 2008). During major events, dust concentrations can exceed 100 $\mu g\ m^{-3}$ (Prospero, 2006; Griffin, 2007). Independent studies using different methodologies have all found a strong positive correlation between dust levels in the Caribbean and periods of drought in the Sahara, while concentrations show a marked decrease during periods of higher rainfall. Consequently, it is argued that higher dust emissions due to increasing aridity in the Sahel and other arid areas could enhance climate change effects over large areas, including the eastern Caribbean and the Mediterranean (Prospero and Lamb, 2003). Similar findings have been reported at Cape Verde where dust emission levels were found to be a factor of nine lower during the decade of the 1950s when rainfall was at or above normal, when compared to the 1980s, a period of intense drought in the Sahel region (Nicoll *et al*., 2011). Dust from the Sahara has also long been known to reach into the eastern Mediterranean (e.g., Santese *et al*., 2010) whilst dust from Asia has been transported across the Pacific and Atlantic oceans and around the world (Uno *et al*., 2009).

There is also evidence that the trans-boundary movement of Saharan dust into the island regions of the Caribbean, Pacific and Mediterranean is associated with various human health problems including asthma admissions in the Caribbean (Monteil, 2008; Monteil and Antoine, 2009; Prospero *et al*., 2008), cardiovascular morbidity in Cyprus in the Mediterranean (Middleton *et al.,* 2008) and is found to be a risk factor in respiratory and obstructive pulmonary disease in the Cape Verde islands (Martins *et al*., 2009). These findings underscore the need for further research into the link between climate change, airborne aerosols and human health in localities, such as oceanic islands far distant from the continental source of the particulates.

29.5.3. Movement and Impact of Introduced and Invasive Species across Boundaries

Invasive species are colonizer species that establish populations outside their normal distribution ranges and spread into natural or local areas. The spread of invasive alien species is regarded as a significant trans-boundary threat to the health of biodiversity and ecosystems, and has emerged as a major factor in species decline, extinction and loss of biodiversity goods and services worldwide. This is particularly true of islands, where both endemicity and vulnerability to introduced species tend to be high (Kenis *et al*., 2009; Reaser *et al*., 2007; Westphal *et al*., 2008; Rocha *et al*., 2009; Kueffer *et al*., 2010). The extent to which alien invasive species successfully establish themselves at new locations in a changing climate will be dependent on many variables, but non-climate factors such as ease of access to migration pathways, suitability of the destination, ability to compete and adapt to new environments, and susceptibility to invasion of host ecosystems are deemed to be critical. This is borne out for example by Le Roux et al. (2008) who studied the effect of the invasive weed *Miconia calvescens* in New Caledonia, Society Islands and Marquesas islands, by Gillespie and Pau (2008) in an analysis of the spread of *Leucaena leucocephala*, *Miconia calvescens*, *Psidium sp*. and *Schinus terebinthifolius* in the Hawaiian islands; and by Christenhusz and Toivonen (2008) who showed the potential for rapid spread and establishment of the oriental vessel fern, *Angiopteris evecta*, from the South Pacific throughout the tropics. Mutualism between an invasive ant

and locally honeydew-producing insects has been strongly associated with damage to the native and functionally important tree species, *Pisonia grandis* on Cousine island,Seychelles (Gaigher, *et al*., 2011).

Whilst invasive alien species constitute a major threat to biodiversity in small islands, the removal of such species can result in recovery and return to species richness. . This has been demonstrated in Mauritius by Baider and Florens, 2011) where some forested areas were weeded of alien plants and after a decade the forest had recovered close to its initial condition,. They concluded, given the severity of alien plant invasion in Mauritius, that their example can 'be seen as a relevant model for a whole swath of other island nations and territories around the world particularly in the Pacific and Indian Oceans' (Baider and Florens, 2011).

The movement of aquatic and terrestrial invasive fauna within and across regions will almost certainly exacerbate the threat posed by climate change in island regions, and could impose significant environmental, economic and social costs. Recent research has shown that the invasion of the Caribbean Sea by the Indo-Pacific lionfish (*Pterois volitans*), a highly efficient and successful predator, is a major contributor to observed increases in algal dominance in coral and sponge communities in the Bahamas and elsewhere in the region. The consequential damage to these ecosystems has been attributed to a significant decline in herbivores due to predation by lionfish (Schofield, 2010; Albins and Hixon, 2008; Lesser and Slattery, 2011; Green *et al.,* 2011). While there is no evidence that the lionfish invasion is climate-related, the concern is that when combined with pre-existing stress factors the natural resilience of Caribbean reef communities would decrease (Albins and Hixon, 2011; Green *et al*., 2012), making them more susceptible to climate change effects such as bleaching. Englund (2008) has documented the negative effects of invasive species on native aquatic insects on Hawai'i and French Polynesia, and their potential role in the extirpation of native aquatic invertebrates in the Pacific. Similarly, there is evidence that on the island of Oahu introduced slugs appear to be 'skewing species abundance in favour of certain non-native and native plants', by altering the 'rank order of seedling survival rates', thereby undermining the ability of preferred species (e.g. the endangered *C. Superba*) to compete effectively (Joe and Daehler, 2008).

29.5.4. Spread of Aquatic Pathogens within Island Regions

The mass mortality of the black sea urchin, *Diadema antillarum*, in the Caribbean basin during the early 1980s demonstrates the ease with which ecological threats in one part of a region can be disseminated to other jurisdictions thousands of kilometres away. The die-off was first observed in the waters off Panama around January 1983, and within 13 months the disease epidemic had spread rapidly through the Caribbean Sea affecting practically all island reefs, as far away as Tobago some 2000 km to the south and Bermuda, some 4000 km to the east. The diadema population in the wider Caribbean declined between 90-95 per cent as a consequence of this single episode (Lessios, 1988, 1995;Rotjan and Lewis, 2008; Alvarez-Filip *et al*., 2009; Croquer and Weil, 2009a, 2009b). As *D. antillarum* is one of the principal grazers that removes macroalgae from reefs and thus promotes juvenile coral recruitment, the collateral damage was severe, as the region's corals suffered from high morbidity and mortality for decades thereafter (Carpenter and Edmunds, 2006; Myhre and Acevedo-Gutierrez, 2007; Idjadi *et al*., 2010).

There are other climate-sensitive diseases such as yellow, white and black band, white plague and white pox that travel across national boundaries and infect coral reefs directly. This is variously supported by examples from the Indo-Pacific relating to the role of bacterial infections in white syndrome and yellow band disease (Piskorska *et al*., 2007; Cervino *et al*., 2008), the impact of microbial pathogens as stressors on benthic communities in the Mediterranean associated with warming seawater (Ainsworth *et al*., 2007; Danovaro *et al*., 2009; Rosenberg *et al*., 2009), and an increasing evidence of white, yellow and black band disease associated with Caribbean and Atlantic reefs (Rosenberg *et al*., 2009; Brandt and McManus, 2009; Miller *et al*., 2009; Weil and Croquer, 2009; McClanahan *et al*,, 2009; Weil and Rogers, 2011).

29.5.5. Trans-Boundary Movements and Human Health

For island communities the trans-boundary implications of existing and future human health challenges are projected to increase in a changing climate. For instance, the aggressive spread of the invasive giant African snail,

Achatina fulica, throughout the Caribbean, Indo-Pacific islands and Hawaii is not only assessed to be a severe threat to native snails and other fauna (e.g. native gastropods), flora and crop agriculture, but is also identified as a vector for certain human diseases such as meningitis (Reaser *et al*., 2007; Meyer *et al*., 2008; Thiengo *et al*., 2010).

Like other aquatic pathogens ciguatoxins, that cause ciguatera fish poisoning, may be readily dispersed by currents across and within boundaries in tropical and sub-tropical waters. Ciguatoxins are known to be highly temperature-sensitive and may flourish when certain sea water temperature thresholds are reached, as has been noted in the South Pacific (Llewellyn, 2010), Cook Islands (Rongo and van Woesik, 2011), Kiribati (Chan *et al*., 2011), the Caribbean and Atlantic (Morrison *et al*., 2008; Otero *et al*., 2010; Tester *et al*., 2010) and Mediterranean (Aligizaki and Nikolaidis, 2008) (see also 29.3.3.3).

29.6. Adaptation and Management of Risks

For most islands, there is limited empirical evidence of changes in risk associated with climate change, largely due to: poor regional projections e.g. of sea level rise (Willis and Church, 2012), and a lack of long term baseline monitoring of changes in climatic risk (Voccia, 2012), such as risk of saline intrusion, risk of invasive species, risk of biodiversity loss, risk of large ocean waves, or risk of sea-level rise. Island adaptation studies therefore rely on analogues of responses to past and present weather extremes and climatic change, or assumed impacts of climate change based on island type, see Table 29-3. Until climate risks are better identified for islands, our ability to identify effective adaptations remains constrained.

[INSERT TABLE 29-3 HERE
Table 29-3. Type of island in the Pacific region and implications for hydro-meteorological hazards.**]**

29.6.1. Addressing Current Vulnerabilities and Adaptation Gaps on Small Islands

There is medium evidence of generic vulnerability of small islands to climate change, with some disagreement about the costs of adapting in small islands, and ultimately the potential need for migration from small islands (Nicholls *et al.,* 2011, Gemenne, 2011, Biermann and Boas, 2010, Voccia 2012). Islands are heterogeneous in geomorphology, culture, ecosystems, populations and hence also in their vulnerability to climate change (Wheeler, 2011). Vulnerabilities and adaptation needs are as diverse as the variety of islands between regions and even within nation states such as the Solomon Islands (see for example Rasmussen *et al.,* 2011).

Generic indices of national level vulnerability continue to emerge (Cardona, 2007) with a minority focused on small islands (e.g. Blancard and Hoarau, 2013). Many indicators suffer from lack of data, for example, Peduzzi et al. (2009) note that 18 small island states in the Pacific, Caribbean and Indian oceans are not included in their Disaster Risk Index due to lack of data. Other generic indices use indicators that are not relevant in all islands (Barnett and Campbell, 2010), or use data of limited quality for islands, such as sea level rise (as used in Wheeler, 2010). Park et al. (2012) attempt to produce relevant indicators of climate vulnerability and adaptive capacity for the Pacific Islands by adopting a three-stage participatory approach linking scientific knowledge with local visions of vulnerability. Their study concludes that all Pacific Island nations will be vulnerable to climate change in the next 40 years.

Following Smit et al. (2000), Brooks et al. (2005), and Yamano et al. (2007), Barnett and Campbell (2010) reinforce the point that island vulnerability to climate change is often a function of four key stressors: socio-economic, geo-physical, and socio-ecological vulnerabilities, as well as the climate stressor. Socio-economic vulnerabilities are related to on-going challenges of managing urbanisation, pollution and sanitation, both in small island states and non-sovereign islands as highlighted by Storey and Hunter (2010) in Kiribati, López-Marrero and Yarnal (2010) in Puerto Rico, and in Mayotte (France) (Le Masson and Kelman, 2011). Geo-physical characteristics of islands are varied, some low-lying atolls, some oceanic, some volcanic islands (see Table 29-3; Figure 29-1), each of which creates different vulnerabilities, for example the Azores (Portugal) face seismic, landslide and tsunami risks (Coutinho *et al*., 2009). Socio-ecological stresses, such as habitat loss and degradation, invasive species (described

in Sax and Gaines, 2008), overexploitation, pollution, human encroachment and disease can harm biodiversity (Caujape-Castells *et al*., 2010; Kingsford *et al.,* 2009), and reduce the ability of socio-ecological systems to bounce back after shocks. To understand climate vulnerability on islands, the impact of each of these non-climate stresses needs to be first understood and then integrated into climate vulnerability assessments (Rasmussen *et al*., 2011). For example, with individual ecosystems, such as coral reef ecosystems – those already under stress from non-climate factors are more at risk from climate change than those that are unstressed (Maina *et al*., 2011, Hughes *et al*., 2003). Evidence is starting to emerge that shows the same applies at the island scale. In Majuro (Marshall Islands), 34-37 years of aerial photography indicates that rural areas have experienced lower rates of erosion than urban areas (Ford, 2012). This could suggest that either the eroding urban coastal areas were initially more exposed, or that human activity in coastal areas and interventions in coastal ecosystems are exacerbating erosion associated with sea level rise. Additional empirical evidence is needed to confirm which explanation is accurate. In short, all aspects of vulnerability and climate risk assessment remain under-researched in islands; for most islands it is not possible to answer the key vulnerability questions unequivocally, i.e. who is at risk of what, where, and when?

29.6.2. Practical Experiences of Adaptation on Small Islands

Islands are often assumed to be generically vulnerable to climate change (Parks and Roberts, 2006, Myers, 2002). Yet islands and islanders are also recognized for their long experience of adapting to weather variability and climate hazards and for their resilience in the face of hydro-meteorological hazards (Barnett, 2001). Their resilience appears to come from both a belief in their own capacity (Kuruppu and Liverman, 2011; Adger and Brown, 2009), and a familiarity with their environment and understanding of what is needed to adapt (Tompkins et al., 2009; Le Masson and Kelman, 2011). For example, compared to communities in the larger countries of Madagascar, Tanzania and Kenya, the Indian Ocean islands – the Seychelles and Mauritius – were found to have comparatively high adaptive capacity (Cinner *et al.,* 2012). Adaptive capacity was assessed as: capacity to anticipate change and prepare strategies, self-awareness of human impact on environment; willingness to change occupation; livelihood diversity; social capital; material assets; access to technology and infrastructure. These studies all point to the importance of self-belief as well as culturally communicated knowledge of current risks and how to respond to them.

There are many ways in which climate adaptation can be undertaken: reducing socio-economic vulnerabilities, building adaptive capacity, enhancing disaster risk reduction, or building longer term climate resilience (e.g. see McGray *et al*., 2007, Eakin *et al*., 2009). Figure 29-5 highlights the potential benefits and risks associated with the various options. Not all adaptations will be equally appropriate in all contexts. Understanding the baseline conditions and stresses (both climate and other) are important in understanding which climate change adaptation option will generate the greatest benefits. On small islands where resources are often limited, recognising the starting point for action is critical to maximising the benefits from adaptation. The following section considers the benefits of pursuing the various options.

[INSERT FIGURE 29-5 HERE
Figure 29-5. Potential benefits and risks associated with alternative climate change adaptation actions or policies.]

29.6.2.1. Building Adaptive Capacity on Small Islands

Capacity to adapt to current risks on islands may be correlated to ability to adapt to future climate change, but there is limited evidence for this (such as Lefale, 2010). Consequently, this section can only assess evidence of adaptive capacity that: reduces vulnerability to existing stressors, enables adaptation to current stresses, or supports current disaster risk management, much of this relates to traditional practices.

As in previous IPCC Assessments, there is continuing strong support for the incorporation of indigenous knowledge into adaptation planning. For example, Samoans have their own seasonal calendar based on observations of local environmental and weather changes. Their ability to forecast the onset of extreme weather and climate events relying predominantly on local environmental changes are tools that could be incorporated in the formulation of climate change adaptation strategies (Lefale, 2010). Two discrete studies from the Solomon Islands highlight the

importance of traditional patterns of social organization within communities to support food security under social and environmental change (Reenberg *et al.,* 2008, Mertz *et al.,* 2010). In both studies the strategy of relying on traditional systems of organization for farming and land use management have been shown to work effectively – largely as there has been little cultural and demographic change. Evidence is inconclusive on the local capacity to observe long-term climate change. In the Solomon Islands, Lauer and Aswani (2010) found mixed ability to detect change in spatial cover of seagrass meadows. In Jamaica, Gamble et al. (2010) reported a high level of agreement between farmers' perception of increasing drought incidence and statistical analysis of precipitation and vegetation data for the area. In this case farmers perceptions clearly validated the observational data and vice versa. Despite some claims that the vulnerability of indigenous groups in small islands may be best tackled by combining indigenous and Western knowledge in a culturally compatible and sustainable manner (Mercer *et al.,* 2007), given the small number of studies in this area, there is not sufficient evidence to determine the benefits and limits to the use of traditional knowledge in building adaptive capacity to climate change on small islands.

There is a growing literature, but a lack of agreement on the role of traditional technologies and skills for climate adaptation. In coastal Samoa participatory village consultation and capacity building that take into account traditional practices, can be vital to the success of adaptation initiatives in island communities (Daly, 2010). Campbell (2009) identified that traditional disaster reduction measures used in Pacific islands focussed around maintaining food security, building community cooperation, and protecting settlements and inhabitants. Examples of actions to maintain food security include: the production and storage of food surpluses – such as yam and breadfruit buried in leaf-lined pits to ferment; high levels of agricultural diversity to minimise specific damage to any one crop; and the growth of robust famine crops – unused in times of plenty which could be used in emergencies (Campbell, 2009). Nonetheless there are physical and cultural limits to the ability to store surplus production on atoll islands. On Rongelap in the Marshall Islands, surpluses are avoided, or are redistributed to support community bonds (Bridges and McClatchey, 2009). Further, traditional approaches that Pacific island communities have used for survival for millennia (such as building elevated settlements and resilient structures; and working collectively), have been abandoned or forgotten due to processes of globalisation, colonialism and development (Campbell, 2009).

Traditional construction methods have long been identified across the Pacific as a means of adapting to tropical cyclones and floods. In the Solomon Islands traditional practices include: elevating concrete floors on Ontong Java to keep floors dry during heavy rainfall events; building 'low, aerodynamic houses and sago palm leaves as roofing material on Tikopia' as preparedness for tropical cyclones; and in Bellona local perceptions are that houses constructed from modern materials and practices are more easily destroyed by tropical cyclones, implying that traditional construction methods are perceived to be more resilient in the face of extreme weather (Rasmussen *et al.,* 2009: 10). In parallel, Campbell (2009) documents the characteristics of traditional building styles (in Fiji, Samoa and Tonga) where relatively steep hipped roofs, well bound connections and joints, and airtight spaces with few windows or doors offer some degree of wind resistance. Traditional building measures can also reduce damages associated with earthquakes – as evidenced in Haiti (Audefroy, 2011). By reducing damage caused by other stresses (such as earthquakes), adaptive capacity is more likely to be maintained. The quality of home construction is critical to its wind-resistance. If inadequately detailed, home construction will fail irrespective of method. While some traditional measures could be challenged as potentially risky – for example using palm leaves, rather than metal roofs as a preparation for tropical cyclone impacts – the documentation of traditional approaches, with an evaluation of their effectiveness remains urgently needed.

Traditional systems appear less effective when multiple civilization-nature stresses are introduced. For example in the island of Makira, Solomon Islands, where there have been high levels of population growth and changing social objectives, these factors appear to have acted as inhibitors of adaptation (Fazey *et al.,* 2011). In Reunion and Mayotte, population growth, and consequent rises in land and house prices have lead low-income families moving closer to hazardous slopes that are prone to landslides and river-banks which are prone to flooding (Le Masson and Kelman, 2011). Traditional belief systems can also limit adaptive capacity, for example in two Fijian villages, approximately half of survey respondents identified divine will as the cause of climate change (Lata and Nunn, 2012). These findings reinforce earlier studies in Tuvalu (Mortreux and Barnett, 2009), and more widely across the Pacific (Barnett and Campbell, 2010). The importance of taking into account local interests and traditional knowledge in adaptation in small islands is emphasized by Kelman and West (2009) and McNamara and Westoby

(2011), yet research is also needed to identify its limits, such as in the context of rapid socio-ecological change, or the impact of belief systems on adaptive capacity.

There remains limited evidence of how traditional knowledge, technologies and skills are being used to support adaptation. To date research in the Pacific and Caribbean dominates small island climate change work. More detailed studies on small islands in the central and western Indian Ocean, the Mediterranean and the central and eastern Atlantic would improve understanding in this area.

29.6.2.2. Addressing Risks on Small Islands

Many of the future climate risks on small islands remain unknown due to: the lack of effective downscaling methods for small islands, the lack of baseline data to ground-truth model results, and the lack of model skill in projecting the climatic variables that matter to small islands, notably: tropical cyclone frequency and intensity, wind speed and direction, precipitation, sea level, ocean temperature and ocean acidification (Brown *et al.,* submitted). Therefore much of the research on climate risks on islands depicts either current hydro-meteorological risks and responses, or risk management for hypothesised risks. In terms of present disaster risks, reflected by global disaster statistics, islands rarely appear to be in the 'worst affected' category - this is due to their small size and population. Yet, when the relative impact of current natural hazards are considered, in terms of percentage of the population exposed or in terms of losses as a percentage of GDP, then islands appear to suffer disproportionately (see Table 29-4).

[INSERT TABLE 29-4 HERE
Table 29-4: Top ten countries in the Asia-Pacific region based on absolute and relative physical exposure to storms and impact on GDP (between 1998 and 2009).]

Much of the climate risks literature recognises the relatively severe impacts of current natural hazards on islands, and identifies a range of approaches for managing this risk. Again, it is worth highlighting that most of this literature considers present day risk as an analogue for future risk; yet there is little evidence of a correlation between the effectiveness of current and future risk management under climate change. Given this constraint, much of the work on addressing risk focuses on either risk transfer, risk spreading or risk avoidance. Risk transfer is often undertaken through insurance; risk spreading through access to and use of common property resources, livelihood diversification, or mutual support through networks; and risk avoidance through migration.

Risk transfer through insurance markets has limited uptake in small islands, as the markets do not function as effectively as they do in larger locations, in part due to a small demand for the insurance products (Heger *et al.*, 2008). In the case of insurance for farmers, researchers found that a lack of demand for insurance products (in their study countries: Grenada, Jamaica, Fiji and Vanuatu) meant an undersupply of customized food insurance products, which in turn contributed to a lack of demand for insurance (Angelucci and Conforti, 2010). Alternatives exist such as index-based schemes which provide pay outs based on the crossing of a physical threshold, e.g. when rainfall drops below a certain level, rather than on drought damage sustained, (Linnerooth-Bayer and Mechler, 2009). The potential for index-based insurance for climate stressors on islands is under-researched. Small island governments also face expensive climate risk insurance. The Caribbean Catastrophe Risk Insurance Facility (CCRIF) pools Caribbean-wide country-level risks into a central, more diversified portfolio – offering lower premiums for participating national governments. CCRIF has been operating since 2007 (CCRIF, 2008). The potential for a similar scheme in the Pacific is being explored (ADB, 2009, Cummins and Mahul, 2009), although there is limited evidence of the long-term effectiveness of index-based or pooled-risk insurance in supporting household level adaptation.

Risk spreading can take many forms from reliance on social networks and familial ties to creation of marine protected areas to enhance representation of habitat types and replication of species. In Fiji, after Cyclone *Ami* in 2003, households whose homes were not affected by the cyclone increased their fishing effort to support those whose homes were damaged (Takasaki, 2011). In this way, risk was spread among the households, and mutual support formed a central pillar for community-based adaptation. In the case of natural systems, risks can be spread through the creation of marine protected areas, around key refuges that protect a diversity of habitat, that cover an

adequate proportion of the habitat and that protect critical areas such as nursery grounds and fish spawning aggregation areas (McLeod *et al.,* 2009). In Fiji, Locally Managed Marine Areas – which involve the local community in the management and protection of their local marine environment – have proven to be effective in increasing biodiversity, and in reducing poverty in areas dependent on marine resources (Techera, 2008). By creating a network of protected areas supported by local communities there is medium evidence that risks associated with some forms of climate change can be spread and potentially reduced (Mills *et al*., 2010).

29.6.2.3. Working Collectively to Address Climate Impacts on Small Islands

More attention is being focused on the relevance and application of community-based adaptation (CBA) principles to island communities, to facilitate adaptation planning and implementation (Warrick, 2009; Kelman *et al*., 2011), and to tackle rural poverty in resource dependent communities (Techera, 2008). Warrick's work in Vanuatu focuses on empowerment that is 'helping people to help themselves', while addressing local priorities and building on local knowledge and capacity. This approach to adaptation is being promoted as an appropriate strategy for small states, since it is something done 'with' rather than 'to' communities (Warrick, 2009).

Nonetheless externally driven programmes to encourage community-level action have produced some evidence of effective adaptation. Both Limalevu et al. (2010) and Dumaru (2010) describe the outcomes of externally-led pilot community-based adaptation projects (addressing water security and coastal management) implemented in villages across Fiji, notably: more effective management of local water resources through capacity building; enhanced knowledge of climate change,-; and, the establishment of mechanisms to facilitate greater access to technical and financial resources from outside the community. Limalevu et al. (2010) recognise that more long term monitoring and evaluation of the effectiveness of community level action is needed.

There is medium evidence that collaboration between a variety of stakeholders can benefit communities through the introduction of technical expertise to avoid simple mistakes that can dampen the effectiveness of adaptation actions. Evidence from the Eastern Caribbean suggests that adaptations taken by individual households to reduce landslide risk – building simple retaining walls – can be ineffective compared to community level responses (Anderson et al., 2011). They argue better hillside drainage through construction of networks of drains to capture surface runoff, household roof-water and grey water, with community support to construct the networks, with input from engineers can significantly reduce landslide risk . Case studies from Fiji and Samoa in which multi-stakeholder and multi-sector participatory approaches were used to help enhance resilience of local residents to the adverse impacts of disasters and climate change (Gero *et al.,* 2011) further support this view. In the case of community based disaster risk reduction (CBDRR), Pelling (2011) notes that buy-in from local and municipal governments are needed, as well as strong pre-existing relationships founded on routine daily activities, to make CBDRR effective. In both the Solomon Islands and the Cayman Islands there is reasonable agreement that the factors that underpin resilience to hazards resonates with earlier work on successful governance of the commons, that is: community cohesion; effective leadership; and, community buy-in to collective action (Schwarz *et al.,* 2011, Tompkins *et al*., 2008). Where community organisations are operating in isolation, or where there is limited coordination and collaboration community vulnerability is likely to increase (Ferdinand *et al*., 2012). Strong local networks, and trusting relationships between communities and government appear to be key elements in adaptation, in terms of maintaining sustainable agriculture and in disaster risk management.

All of these studies reinforce the earlier work of Barnett (2001), providing robust evidence that supporting community-led approaches to disaster risk reduction and hazard management may contribute to greater community engagement with anticipatory adaptation. However, it is not yet possible to identify the extent to which climate resilience is a coincidental benefit of island lifestyle and cultural, or a purposeful approach, such as the community benefits gained from reciprocity among kinship groups (Campbell, 2009).

29.6.2.4. Addressing Long-Term Climate Impacts and Migration on Small Islands

Small island states have 16% of their land area in low elevation coastal areas (<10m) as opposed to a global average of 2%, and the largest proportion of low elevation coastal urban land area: 13% (along with Australia and New Zealand), in contrast to the global average of 8% (McGranahan *et al.,* 2007). Figures like these lead many to suggest that small islands could be overwhelmed by rising seas associated with sea level rise (Loughry and McAdam, 2008, Yamamoto and Esteban, 2010, Gordon-Clark, 2012, Berringer, 2012, Dema, 2012, Lazrus, 2012, Laczko and Aghazarm, 2009). Yet there remains limited evidence as to which regions (Caribbean, Pacific, Indian Ocean) will experience the largest sea level rise (Willis and Church, 2012), which islands will experience the worst climate impacts, or which, if any, islands might disappear completely. Nicholls et al. (2011) have modeled impacts of 4°C warming, producing a 0.5 to 2.0m sea level rise, to assess the impacts on land loss and on migration. With no adaptation occurring, they estimate that this could produce displacement of between 1.2 and 2.2 million people from the Caribbean, Indian Ocean and Pacific Ocean. More research is needed to produce robust agreement on the impact of sea level rise on small islands, and on the range of adaptation strategies that could be appropriate under those scenarios. Some authors highlight that the image of small islands as 'canaries in the coal mine' is a western discourse that could potentially hinder adaptation in islands (Farbotko and Lazrus, 2012). Research into the possible un-inhabitability of islands has to be undertaken sensitively to avoid short-term risks (i.e. to avoid depopulation and ultimately island abandonment) associated with a loss of confidence in an islands' future (McNamara and Gibson, 2009, McLeman, 2011).

Relocation and displacement are frequently cited as outcomes of sea level rise and consequent land loss on islands (Byravan and Rajan, 2006, Biermann and Boas, 2008, Kolmannskog and Trebbi, 2010). Recent examples of environmental stress driven relocation and displacement provide contemporary analogues of climate-induced migration. Evidence of post-natural disaster migration has been documented in the Caribbean in relation to hurricanes (McLeman and Hunter, 2010), and in the Carteret Islands, Papua New Guinea – where during exceptionally high inundation event in 2008 (see 29.5.1.1) islanders sought refuge on neighbouring Bougainville island (Jarvis, 2010). Drawing any strong conclusions from this literature is challenging as there is little understanding of how to measure the effect of the environmental signal in migration patterns (Afifi *et al.*, 2013, Krishnamurthy, 2012). While the example of the Carteret Islands cannot be described as evidence of adaptation to climate change, it suggests that under some scenarios entire island communities may need to relocate in the future (Gemenne, 2011). In reality, financial and legal barriers are likely to inhibit significant levels of international environmentally induced migration in the Pacific (Barnett and Chamberlain, 2010) (see also Box 29-1). In the event of entire island relocation, the international community could find itself confronted with other critical issues such as how to support the legal and political continuity of a state that has lost its territory (Cournil and Gemenne, 2010). The potential migration options open to islands are presented in Table 29-5.

[INSERT TABLE 29-5 HERE
Table 29-5: Climate migration options in the Pacific.]

Climate stress is occurring at the same time as the growth in rural to urban migration. The latter is leading to squatter settlements that strain urban infrastructure – notably: sewerage, waste management, transport and electricity (Jones, 2005, Connell and Lea, 2002). Urban squatters often live in highly exposed locations, lacking basic amenities, leaving them highly vulnerable to climate risks (Baker, 2012). There is however limited evidence of the impact of climate change on the growing number of urban migrants in islands.

29.6.3. Barriers and Limits to Adaptation in Small Island Settings

Since publication of the IPCC SAR in 1996, significant barriers to climate change adaptation strategies in island settings have been discussed in considerable detail. Barriers include inadequate access to financial, technological and human resources, issues related to cultural and social acceptability of measures, constraints imposed by the existing political and legal framework, the emphasis on island development as opposed to sustainability, and a tendency to focus on addressing short term climate variability rather than long term climate change, and community preferences for "hard" adaptation measures (seawalls i.e.) instead of "soft" devices (Sovacool 2012). Heger et al.

(2008) recognise that more diversified economies have more robust responses to climate stress, yet most small islands lack economies of scale in production, thus specialising in niche markets and developing monocultures (e.g. sugar or bananas). Non-sovereign island states face additional exogenous barriers to adaptation. For example, islands like Réunion and Mayotte experience French provision of social services, but not the French level of building codes and land use planning (Le Masson and Kelman, 2011). Owing to their nature and complexity, these constraints will not be easily eliminated in the short term and will require on-going attention if their impact is to be minimized incrementally over time. Exogenous factors, such as the comparatively few assessments of social vulnerability to climate change, adaptation potential or resilience for island communities (Barnett, 2010) limit current understanding and action. In part this is due to the particularities of islands – both their heterogeneity and their difference from mainland locations – as well as the limitations of climate models in delivering robust science for small islands. It remains the case that thirteen years after Nurse et al. (2001) noted that downscaled global climate models do not provide a complete or necessarily accurate picture of climate vulnerabilities on islands, there is still little climate impacts research that reflects local concerns and contexts (Barnett *et al.,* 2008).

While lack of access to adequate financial, technological and human resources is often cited as the most critical constraint, experience has shown that endogenous factors such as culture, ethics, knowledge and attitudes to risk are important in constraining adaptation. Translating the word 'climate' into Marshallese implies cosmos, nature and culture as well as weather and climate (Rudiak-Gould, 2012), such cultural misunderstandings can create both barriers to action and novel ways of engaging with climate change. The lack of local support (due to encroachment on traditional lands) for the development of new infiltration galleries to augment freshwater supply on Tarawa atoll, Kiribati, highlights the importance of social acceptability (Moglia *et al.,* 2008a, 2008b). Such considerations have led to the conclusion that there is still much to be learned about the drivers of past adaptation and how 'mainstreaming' into national programs and policies, widely acclaimed to be a virtually indispensable strategy, can practically be achieved (Mercer *et al.,* 2007; Adger *et al.,* 2009; Mertz *et al.,* 2009).

Notwithstanding the extensive and ever-growing body of literature on the subject, there is still a relatively low level of awareness and understanding at the community level on many islands about the nature of the threat posed by climate change (Nunn, 2009). Even where the threat has been identified, it is often not considered an urgent issue, or a local priority, as exemplified in Malta (Akerlof *et al.,* 2010), and Funafuti, Tuvalu (Mortreux and Barnett, 2009). Lack of awareness, knowledge and understanding can function as an effective barrier to the implementation and ultimate success of adaptation programs. This is borne out in both Fiji and Kiribati where researchers found that spiritual beliefs, traditional governance mechanisms, and a short term approach to planning were barriers to community engagement and understanding of climate change (Kuruppu, 2009, Lata and Nunn, 2012). Although widely acknowledged to be critical in small islands, few initiatives pay little more than perfunctory attention to the importance of awareness, knowledge and understanding in climate change adaptation planning. Hence, the renewed call for adaptation initiatives to include and focus directly on these elements on an ongoing basis (e.g., Crump, 2008; Kelman and West, 2009; Kelman, 2010; Kuruppu and Liverman, 2011; Gero *et al.,* 2011) is timely, if these barriers are to be eventually removed.

29.6.4. Mainstreaming and Integrating Climate Change into Development Plans and Policies

There is a growing body of literature that discusses the benefits and possibilities of mainstreaming or integrating climate change policies in development policies. Various mechanisms through which development agencies as well as donor and recipient countries can seek to capitalize on the opportunities to mainstream are beginning to emerge (see for example Klein *et al.,* 2007; Mertz *et al.,* 2009). Agarwala and van Aalst (2008) provide examples from Fiji and elsewhere, of where synergies (and trade-offs) can be found in integrating adaptation to climate change into development cooperation activities, notably: disaster risk reduction, community-based approaches to development, and building adaptive capacity. Boyd et al. (2009) urge for more rapid integration of adaptation into development planning, to ensure that adaptation is not side-lined, or treated separately from sectoral policies. Although there are synergies and benefits to be derived from the integration of climate change and development policies, care is needed to avoid institutional overlaps, and differences in language and approach – which can give rise to conflict (Schipper and Pelling, 2006). Overall however, there appears to be an emerging consensus around the views expressed by Swart and Raes (2007) that climate change and development strategies should be considered as complementary, and

that some elements such as land and water management and urban planning provide important adaptation, development and mitigation opportunities.

29.7. Adaptation and Mitigation Interactions

Greenhouse gas emissions from most small islands are negligible in relation to global emissions, yet small islands will most probably be highly impacted by climate change (Srinivasan, 2010). Since small islands' populations are not responsible for anthropogenic climate change there is little moral imperative for them to reduce greenhouse gas emissions, though most have chosen to do so because of the potential co-benefits and synergies. Malta and Cyprus are obliged to do so in line with EU climate and energy policies. This section considers some of the inter-linkages between adaptation and mitigation on small islands and the potential synergies, conflicts, trade-offs and risks. Unfortunately there is relatively little research on the emissions reduction potential of small islands, and far less on the inter-linkages between climate change adaptation and emissions reduction in small islands. Therefore in this section a number of assumptions are made about how and where adaptation and mitigation actions interact.

29.7.1. Assumptions/Uncertainties Associated with Adaptation and Mitigation Responses

Small islands are not homogeneous, they have diverse geo-physical characteristics and economic structures (see Table 29-3, Figure 29-1). Following Nunn (2009) we assume that the combination of island geography and economic types informs the extent to which adaptation and mitigation actions might interact. The geography and location of islands affect their sensitivity to hydro-meteorological and related hazards such as cyclones, floods, droughts, invasive alien species, vector borne disease, and landslides. On the other hand the capacity of island residents to cope is often related income levels, resources endowment, technology and knowledge (see 29.6.2).

The costs of adaptation in small islands are likely to be relatively large, mostly due to the problem of overhead cost indivisibilities (see 29.3.3) and also because of the potentially high climate change impacts. Bueno et al. (2008) examined the potential costs to the island nations of the Caribbean if greenhouse gas emissions continue unchecked and found that for just three categories—increased hurricane damages, loss of tourism revenue, and infrastructure damages—the Caribbean's annual cost of inaction is projected to total $22 billion annually by 2050 and $46 billion by 2100. These costs represent 10 per cent and 22 per cent, respectively, of the current Caribbean economy.

The potential for mitigation and emissions reductions in islands depends to a large extent on their size and stage of economic development. In the small and less developed islands key 'mitigation' sectors: including energy, transport, industry, built environment, agriculture, forestry, or waste management sectors are likely to be relatively small (Metz *et al.,* 2007, Swart and Raes, 2007). Hence opportunities for emissions reductions are usually quite limited and are mostly associated with electricity generation and utilization of vehicles. More mitigation opportunities should exist in more economically advanced and larger islands that rely on forms of production that utilize fossil fuels, including manufacturing, and where vehicle usage is extensive and electricity driven home appliances, such as air conditioners and water heaters, are extensively used. Table 29-6 presents an indicative assessment of potential areas for mitigation activity on small islands by island 'economy type'.

[INSERT TABLE 29-6 HERE
Table 29-6. Economic structure of small islands and areas of potential emissions reduction.]

In the absence of significant mitigation efforts at the global scale, adaptation interventions could become very costly and difficult to implement, once certain thresholds of change are reached. (Nelson, 2011; Rosenzweig and Wilbanks, 2010, Thornton *et al.,* 2011, Birkmann, 2011). Nicholls et al. (2011) make a similar observation with respect to coastal protection as a response to sea level rise. They suggest that if global mean temperatures increase by around 4^0 C (which may lead to sea level rise between 0.5 m and 2 m) the likelihood of successful coastal protection in some locations such as low-lying small islands, will be low. Consequently, it is argued that 'coastal abandonment' would be a likely outcome in such circumstances (Nicholls *et al.,* 2011).

29.7.2. Potential Synergies and Conflicts

Metz et al. (2007) suggest that adaptation and mitigation interactions occur in one of four main ways: adaptations that result in greenhouse emissions reduction,; mitigation options that facilitate adaptation; policy decisions that couple adaptation and mitigation effects; and, trade-offs and synergies between adaptation and mitigation. Each of these opportunities is considered using three examples: coastal forestry, energy supply, and tourism.

Small islands have relatively large coastal zones (in comparison to land area) and most development (as well as potential mitigation and adaptation activities) are located in the coastal zone. Coastal ecosystems (coral reefs, sea grasses and mangroves) play an important role in protecting coastal communities from wave erosion, tropical cyclones, storm surges, and even moderate tsunami waves (Cochard *et al*., 2008). Whilst coastal forests including both endemic and exotic species especially mangroves are seen as effective adaptation options ('bioshields' Feagin *et al*..2010) in the coastal zones, they also play an important role in mitigation as carbon sinks (van der Werf *et al*., 2009). Thus, the management and conservation of mangrove forests has the potential to generate synergies between climate change adaptation and mitigation. However, despite this knowledge population, development and agricultural pressures have constrained the expansion of island forest carbon stocks (Fox *et al*., 2010) while Gilman et al. (2008) note that such pressures can also reduce the buffering capacity of coastal vegetation systems.

Renewable energy resources on small islands have only recently been considered within the context of long-term energy security (Praene *et al*., 2012, Chen *et al*., 2007). Stuart (2006) speculates that the lack of uptake of renewable technologies to date might be due to historical commitments to conventional fossil fuel-based infrastructure, and a lack of resources to undertake research and development of alternatives. Those islands that have introduced renewable energy technologies have often done so with support from international development agencies (Dornan, 2011). Despite thisthere remain significant barriers to the wider institutionalization of renewable technologies in small islands. Research in Europe and the United States has shown the mitigation and cost savings benefits of Energy Service Companies (ESCOs): companies that enter into medium-to-long term performance-based contracts with energy users, invest in energy efficiency measures in buildings and firms, and profit from the ensuing energy savings measures for the premises (see for example Steinberger *et al*., 2009). Potential benefits exist in creating the opportunity for ESCOs to operate in small islands. Preliminary evidence from Fiji suggests that if the incentive mechanisms can be resolved, and information asymmetries between service providers and users can be aligned, ESCOs could provide an opportunity to expand renewable technologies (Dornan, 2009).

The transition towards renewable energy sources away from fossil fuel dependence has been partly driven by economic motives, notably to avoid oil price volatility and its impact. The development of hydro-power (in Fiji for example) necessitates protection and management of the water catchment zones, and thus could lead to improved management of the water resources – a critical adaptation consideration for areas expected to experience a decrease in average rainfall as a result of climate change. Whilst the cost effectiveness of renewable technologies is critical, placing it within the context of water adaptation could enhance project viability (Dornan, 2009). Cost-benefit analyses have shown that in southeast Mediterranean islands photovoltaic generation and storage systems may be more cost-effective than existing thermal power stations (Kaldellis, 2008; Kaldellis *et al*., 2009).

Energy prices in small islands are among the highest anywhere in the world, mainly due to their dependence on imported fossil fuel, and limited ability to reap the benefits of economies of scale including bulk buying. Recent studies show that the energy sectors in small islands may be transformed into sustainable growth entities mainly through the judicious exploitation of renewable energy sources, combined with the implementation of energy efficiency measures (van Alphen *et al*., 2008; Banuri, 2009; Mohanty, 2012; Rogers *et al*., 2012). Realising the potential for such transformation, the countries comprising the Alliance of Small Island States (AOSIS) launched SIDS Dock, which is intended to function as a 'docking station' to connect the energy sector in SIDS with the international finance, technology and carbon markets with the objective of pooling and optimizing energy efficiency goods and services for the benefit of the group. This initiative seeks to decrease energy dependence in SIDS, while generating financial resources to support low carbon growth and adaptation interventions.

Many small islands rely heavily on the foreign exchange from tourism to expand and develop their economies, including the costs of mitigation and adaptation. Tourism, particularly in small islands, often relies on coastal and terrestrial ecosystems o provide visitor attractions and accommodation space. Much has been made of the relationship between ecosystem services and tourism In Jamaica, Thomas-Hope and Jardine-Comrie (2007) suggest that sustainable tourism planning should include activities undertaken by the industry, that is tertiary treatment of waste, and re-use of water, as well as composting organic material and investing in renewable energy. Gossling and Schumacher (2010) and others who have examined the linkages between greenhouse gas emissions and sustainable tourism argue that the tourism sector (operators and tourists) should pay to promote sustainable tourism, especially where they benefit directly from environmental services sustained by these investments.

29.8. Facilitating Adaptation and Avoiding Maladaptation

While there is a clear consensus that adaptation to the risks posed by global climate change is necessary and urgent in small islands, the implementation of specific strategies and options is a complex process that requires critical evaluation of multiple factors, if expected outcomes are to be achieved (Kelman and West, 2009; Barnett and O'Neill, 2012). These considerations may include, *inter alia*, prior experience with similar or related threats, efficacy of the strategies or options and their co-benefits, costs (monetary and non-monetary), availability of alternatives and social acceptability. In addition, previous work (e.g. Adger *et al.,* 2005) has emphasized the relevance of scale as a critical factor when assessing the efficacy and value of adaptation strategies, as the extent to which an option is perceived to be a success, failure or maladaptive may be conditioned by whether it is being assessed as a response to climate variability (shorter-term) or climate change (longer-term).

As in other regions, adaptation in islands is locally delivered and context specific (Tompkins *et al.,* 2010). Yet, sectors and communities on small islands are often so intricately linked that there are many potential pathways that may lead to maladaptation, be it via increased greenhouse gas emissions, foreclosure of future options, burdensome opportunity costs on local communities, by unintentionally discouraging adaptation initiatives, or by fostering over-dependence on external support (see for example Box 29-1).

_____ START BOX 29-1 HERE _____

Box 29-1. Resettlement and Migration: Adaptation or Maladaptation?

Whilst there is agreement that assistance from the international community is vital for supporting adaptation programs in small islands, there is a concern that some types of interventions may actually be maladaptive. For example, Barnett and O'Neill (2012) suggest that strategies such as resettlement and migration should be regarded as options of 'last resort' on islands, as they may actually discourage viable adaptation initiatives, by fostering over-dependence on external support. They argue that in the Pacific islands

> "Relying on resettlement forecloses on all other adaptation options…if there is no future for people in the places in which they live, then there is no reason to manage those places sustainably…Thus, if the only answer to climate change is resettlement, then there is no need to do anything else but wait, all other adaptation options will become impossible, and incentives to reduce greenhouse gas emissions will be similarly reduced" (Barnett and O'Neill, 2012, p.10)

_____ END BOX 29-1 HERE _____

Notwithstanding the observations of Barnett and O'Neill (2012), there is a concern that early foreclosure of this option might well prove maladaptive, if location-specific circumstances show such action to be efficacious in the longer-term. States contemplating this option may wish to consider early proactive planning, as resettlement of entire communities might prove to be socially, culturally and economically disruptive (Campbell, 2010; McMichael *et al.,* 2012; refer also to 29.3.3.4). The case study of the residents of Nauru who contemplated resettlement in Australia after the collapse of phosphate mining (their only revenue source) in the1950s, provides helpful insight

about the complex social, economic and cultural challenges associated with environmentally triggered migration (Tabucanon and Opeskin, 2011). The challenge therefore is to find the middle ground between premature resettlement and objective assessment of other appropriate adaptation choices.

Similarly, while insurance is being promoted as an element of the overall climate change response strategy in some island regions, e.g. the Caribbean, where the Caribbean Catastrophe Risk Insurance Facility (a multi-country risk pooling facility established in 2007 and owned by Caribbean governments) has been implemented, concerns have also been expressed in various jurisdictions about possible linkages to maladaptation. The potential consequences include the imposition of exorbitant premiums that are beyond the capacity of resource-scarce governments as the perception of climate change risks increase, discriminatory coverage of sectors that may not align with local priorities, and tacit encouragement for the state, individuals and the private sector to engage in behavior that is not risk-averse, e.g. development in hazard-prone areas (Herweijer*et al.,* 2009; Linnerooth-Bayer *et al.,* 2009; Linnerooth-Bayer *et al.,* 2011; van Nostrand and Nevius, 2011; Thomas and Leichenko, 2011). Likewise, although the exploitation of renewable energy is vital to the sustainable development of small islands, more attention needs to be paid to the development of energy storage technologies, if rapid transition from conventional fuels is to be achieved in an efficient manner. This is especially important in the case of intermittent energy sources (e.g. solar and wind), as the cost of current storage technologies can frustrate achievement of full conversion to renewables. Thus to avoid the possibility of maladaptation in the sector, countries may wish to consider engaging in comprehensive planning, including considerations relating to energy storage (Krajačić *et al.,* 2008; Krajačić *et al.,* 2010; Bazilian *et al.,* 2011).

Recent studies have demonstrated that opportunities exist in island environments for avoiding maladaptation. Studies have shown for example that decisions about adaptation choices and their implementation are best facilitated where there is constructive engagement with the communities at risk, in a manner that fosters transparency and trust (Fazey *et al.,* 2008; Lopez Marrero, 2010; van Aalst et al., 2008). Further, some analysts argue that adaptation choices are often subjective in nature and suggest that participatory stakeholder involvement can yield valuable information about the priorities and expectations that communities attach to the sector for which adaptation is being sought. The point is underscored by Moreno and Becken (2009), whose study of the tourism sector on the Mamanuca islands (Fiji) clearly demonstrates that approaches which explicitly integrate stakeholders into each step of the process from vulnerability assessment right through to consideration of alternatives measures can provide a sound basis for assisting destinations with the implementation of appropriate adaptation interventions. This view is supported by Dulal *et al*. (2009), who argue that the most vulnerable groups in the Caribbean - the poor, elderly, indigenous communities and rural children – will be at greater risk of being marginalized, if adaptation is not informed by equitable and participatory frameworks.

Other studies reveal that new paradigms whose adoption can reduce the risk of maladaptation in island environments, are emerging across various sectors. In the area of natural resource management, Hansen *et al*. (2010) suggest that the use of protected areas for climate refugia, reduction of non-climate stressors on ecosystems, adoption of adaptive management approaches combined with reduction of greenhouse gas emissions wherever possible, may prove to be more effective response strategies than traditional conservation approaches. Other strategic approaches, including the implementation of multi-sectoral and cross-sectoral measures, also facilitate adaptation in a more equitable, integrated and sustainable manner. Similarly, '*no-regret'* measures such as wastewater recycling, trickle irrigation, conversion to non-fossil fuel based energy and transportation which offer collateral benefits with or without the threat of climate change, and '*low-regret'* strategies, which may only increase existing operational costs marginally, are becoming increasingly attractive options to island governments (Gravelle and Mimura, 2008; Heltberg *et al.,* 2009; Cashman *et al.,* 2010; Howard *et al.,* 2010). Together, these constitute valid risk management approaches, as they are designed to assist communities in making prudent, but necessary decisions, in the face of an uncertain future.

Caution is needed to ensure that donors are not driving the adaptation and mitigation agenda in small islands, as there is a risk that donor-driven adaptation or mitigation will not address the salient challenges on small islands, and may lead to inadequate adaptation or a waste of scarce resources (Barnett, 2010; Nunn, 2009). There is a concern that donor-led initiatives may unintentionally cause enhanced vulnerability by supporting adaptation strategies that

are externally derived, rather than optimizing the benefits of local practices that have proven to be efficacious through time (Reenberg *et al.,* 2008; Kelman and West, 2009; Campbell and Beckford, 2009).

29.9. Research and Data Gaps

Significant advances in our understanding of the actual impacts and potential effects of climate change on small islands have been made since the AR4. These advances cover a range of themes including: dynamic downscaling of scenarios appropriate for small islands; impacts of trans-boundary processes generated well beyond the borders of an individual nation or island; barriers to adaptation in small islands and how they may be overcome; the relationships between climate change adaptation and disaster risk reduction; and, the relationships between climate change adaptation, maladaptation and sustainable development.

It is also evident that much further work is required on these topics in small island situations, especially comparative research. There are also important information and data gaps and many uncertainties still exist on impacts, vulnerability and adaptation in small islands. These include:

- **Lack of climate change and socio-economic scenarios and data at the required scale for small islands**. For example, projected changes in climate for the Caribbean, Pacific, Indian Ocean and Mediterranean islands, generally apply to the region as a whole and not to specific countries. However, most socio-economic decisions are taken at smaller scales. There is need for credible simulations of future small island climates and socio-economic conditions at comparable scales
- **Difficulties in detecting and attributing past impacts on small islands to climate change processes.** Further investigation of the observed impacts of weather, climate and ocean events that may be related to climate change is required to clarify the relative role of climate change and non-climate change drivers.
- **Uncertainty about the potential impacts of climate change**. In several small islands adaptation is being progressed without adequate understanding of past or potential impacts and vulnerability. Whilst assessment of future impacts is hampered because of uncertainty in climate projections at the local island level, alternative scenarios could be used for vulnerability and sensitivity studies to guide adaptation strategies.
- **Need for a range of climate change-related projections beyond temperature and sea-level.** Generally climate-model projections of temperature and sea-level have been satisfactory, but there are strong requirements for projections for other variables that are of critical importance to small islands. These include rainfall and drought, wind direction and strength, tropical storms and wave climate, and recognition that trans-boundary processes are also significant in a small island context.
- **Need to acknowledge the heterogeneity and complexity of small island states and territories.** Although small islands have several characteristics in common, neither the variety or complexity of small islands is sufficiently appreciated. Thus, transferring data and practices from a continental situation, or from one small island state to another, needs to be done with care.
- **Need to develop a typology that classifies small island states into a few groupings based on their social, cultural, economic, physical and ecological characteristics relevant to climate change impacts and vulnerability**. This has been an elusive task to date noting the discussion on vulnerability indicators in 29.6.1. Notwithstanding that discussion as well as the foregoing point there is increasing evidence that such a typology could be developed in stages. For example, an improved understanding of the interactions between vulnerability and 'island type' could provide useful guidance for optimizing scarce adaptation resources at community and local levels.
- **Within country/territory differences need to be better understood**. Many of the environmental and human impacts we have reported have been attributed to the whole country, when in fact they refer only to the major centre or town or region. There is need for more work on rural areas, outer islands and secondary communities. Several examples of such research have been cited in this chapter. Also it should be noted that some small island states are single islands and others highly fragmented multiple islands.
- **Lack of investment and attention to climate and environmental monitoring frameworks in small islands**. A fundamental gap in the ability to improve empirical understanding of present and future climate change impacts is the lack of climate and environmental monitoring frameworks that in turn hampers the level of confidence with which adaptation responses can be designed and implemented.

- **Economic and social costs of climate change impacts and adaptation options are rarely known**. In small island states and territories the costs of past weather, climate and ocean events is poorly known and further research is required to identify such costs, and to determine the economic and societal costs of climate change impacts and the costs of adaptation options to minimize those impacts.
- **Need to integrate adaptation to climate change and development co-operation activities.** There is some evidence to indicate that longer-term climate change adaptation policies and programs in small islands are compromising more immediate development objectives. Avenues need to be developed to redress this situation perhaps through a combined focus on hazard risk reduction and community based approaches to development and adaptation. Synergies between adaptation and development need to be explored in a small island context.

The foregoing list is a sample of the gaps, needs and research agenda appropriate for small island states. If those gaps are filled, needs satisfied and research achieved, we feel that the general view that small islands are highly vulnerable to climate change, and, that they have low adaptive capacity, may well be challenged by some nations as well as in some sectors and/or regions within small island states.

Frequently Asked Questions

FAQ 29.1: Are small islands experiencing the impacts of climate change?

Observed impacts of climate change on small islands are not conclusive. Whilst the media and some researchers emphasize the vulnerability of small islands, there are few studies that have been able to isolate anthropogenically-induced climate change impacts from those associated with natural climate variability and/or human activities. Even in the case of atolls where inundation from sea-flooding, storm surges and shoreline erosion has occurred, sea-level rise specifically linked to climate change has not been definitively identified as a primary cause of these hazards, or of outmigration and resettlement of populations from such areas. This does not mean that small islands are not experiencing the physical and socio-economic impacts of climate change, but rather that the manifestation of any climate change impact is not easily distinguishable from impacts attributable to other possible causes. It also reflects the poor level of empirical monitoring which occurs in small island environments and represents a research gap that needs to be urgently filled if greater confidence in the attribution of climate change stress in both human and physical systems is to be achieved.

FAQ 29.2: Why is it difficult to detect and attribute changes on small islands to climate change?

In the last two or three decades many small islands have undergone substantial changes in human settlement patterns and in socio-economic and environmental conditions. Such changes may have masked any clear evidence of climate change. This has resulted in difficulties when attempting to detect and attribute changes on small islands to climate change. One example can be cited. In many small islands coastal erosion has been widespread and has adversely affected important tourist facilities, settlements, utilities and infrastructure. However, specific case studies from islands in the Pacific and Indian oceans and the Caribbean have indicated that attribution of such shoreline instability to factors like sea-level rise associated with climate change have been masked by pervasive human impacts as well as episodic extreme events. Whilst coastal erosion is consistent with models of sea-level rise resulting from climate change, it has not been possible to quantify the extent of attribution of past and on-going coastal erosion to that factor. Given the range of natural processes and human activities that could impact the coasts of small islands in the future, the role of climate change-related processes may continue to be difficult to quantify and attribute.

FAQ 29.3: Why is the cost of adaptation to climate change so high in small islands?

Adaptation to climate change often involves overhead costs, such as infrastructural changes and upgrades. These generally include ‘lumpy‘ costs and costs that cannot be downscaled in proportion to the size of the population or territory. This disadvantage, termed the ‘indivisibility’ problem, is a major socio-economic issue for many small islands. It can be illustrated by way of example. A seawall, intended as a shore protection measure, 100 m long, suitable for a small island, will cost much more than one-tenth of a seawall 1 km long (that is ten times as much), suitable for a larger territory. This means that the cost of the seawall to the small island will be higher per m than for the larger territory. This reality applies throughout much of a small island economy including the

indivisibility of public utilities and services. It also applies to all forms of development and redesign of the infrastructure, aimed at ensuring that it is more resilient to climate change and extreme weather events. The result is a relatively higher adaptation cost per capita in countries with small populations, such as small islands and especially those islands that are geographically isolated, have a poor resource base and high import and transport costs.

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Table 29-1: Small islands regions temperature and precipitation change projections for the SRES A1B scenario over the period 2080-2099 compared to 1980-1999. The table shows the minimum, median (50%), and maximum values of the mean temperature and precipitation responses from each of the 21 AR4 global models (adapted from WGI AR4 Table 11.1).

Small Island Region	**Season (by month)**	**Temperature Change (ºC)**			**Precipitation Change (%)**		
		min	median	max	min	median	max
Caribbean	DJF	1.4	2.1	3.2	-21	-6	10
	MAM	1.3	2.2	3.2	-28	-13	6
	JJA	1.3	2.0	3.2	-57	-20	8
	SON	1.6	2.0	3.4	-38	-6	19
	ANNUAL	1.4	**2.0**	3.2	-39	**-12**	11
Indian Ocean	DJF	1.4	2.1	3.8	-4	4	20
	MAM	1.5	2.2	3.8	0	5	20
	JJA	1.4	2.1	3.7	-3	3	20
	SON	1.4	2.0	3.6	-5	4	21
	ANNUAL	1.4	**2.1**	3.7	-2	**4**	20
North Pacific	DJF	1.5	2.4	3.6	-5	3	17
	MAM	1.4	2.3	3.5	-17	1	17
	JJA	1.4	2.3	3.9	1	8	25
	SON	1.6	2.4	3.9	1	6	22
	ANNUAL	1.5	**2.3**	3.7	0	**5**	19
South Pacific	DJF	1.4	1.8	3.2	-6	4	15
	MAM	1.4	1.9	3.2	-3	6	17
	JJA	1.4	1.8	3.1	-2	3	12
	SON	1.4	1.8	3.0	-8	2	5
	ANNUAL	1.4	**1.8**	3.1	-4	**3**	11

Table 29-2: Preliminary projected percentage changes in tuna catches relative to the 20 year average (1980-2000) and estimated percentage change to government revenue resulting from projected changes in the catch of skipjack tuna in 2030 and 2100 (Bell et al., 2011).

SRES Scenario		2035	2100	
		B1/A2	B1	A2
Skipjack tuna	Western fishery	+ 11%	-0.2%	-21%
	Eastern fishery	+37%	+43%	+27%
Bigeye tuna	Western fishery	-2%	-12%	-24%
	Eastern fishery	+3%	-4%	-18%
Skipjack tuna	Total	+19%	+12%	-7%
Bigeye tuna	Total	+0.3%	-9%	-27%
Change to Government Revenue (Percent)	FSM	0.8 to 1.7%	-0.9 to -1.9%	
	Solomon Is	0.01 to 0.16%	-0.03 to0.77%	
	Kiribati	+11 to 18.4%	+7.2 to12.0%	
	Tuvalu	+3.7 to 9.2%	+2.5 to6.2%	

Table 29-3: Type of island in the Pacific region and implications for hydro-meteorological hazards.

Island type and size	Island elevation, slope, rainfall	Implications for hazard
Continental - Large - High biodiversity - Well developed soils	- High elevations - River flood plains - Orographic rainfall	River flooding more likely to be a problem than in other island types. In PNG high elevations expose areas to frost (extreme during El Nino).
Volcanic High Islands - Relatively small land area - Barrier reefs - Different stages of erosion	- Steep slopes - Less well developed river systems - Orographic rainfall	Because of size few areas are not exposed to tropical cyclones. Streams and rivers subject to flash flooding. Barrier reefs may ameliorate storm surge.
Atolls - Very small land area - Small islets surround a lagoon - Larger islets on windward side - Shore platform on windward side - No or minimal soil	- Very low elevations - Convectional rainfall - No surface (fresh) water - Ghyben Herzberg (freshwater) lens	Exposed to storm surge, 'king' tides and high waves. Narrow resource base. Exposed to fresh water shortages and drought. Water problems may lead to health hazards.
Raised Limestone Islands - Concave inner basin - Narrow coastal plains - No or minimal soil	- Steep outer slopes - Sharp karst topography - No surface water	Depending on height may be exposed to storm surge. Exposed to fresh water shortages and drought. Water problems may lead to health hazards.

Source: Campbell (2009:89)

Table 29-4: Top ten countries in the Asia-Pacific region based on absolute and relative physical exposure to storms and impact on GDP (between 1998 and 2009).

Rank	Absolute exposure (millions affected)	Relative exposure (% of the population)	Absolute GDP loss ($billions)	Loss (as a % of GDP)
1	Japan (30.9)	**North Mariana Isls (58.2)**	Japan (1,226.7)	**North Mariana Isl (59.4)**
2	Philippines (12.1)	**Niue (25.4)**	Rep. of Korea (35.6)	**Vanuatu (27.1)**
3	China (11.1)	Japan (24.2)	China (28.5)	**Niue (24.9)**
4	India (10.7)	Philippines (23.6)	Philippines (24.3)	**Fiji (24.1)**
5	Bangladesh (7.5)	**Fiji (23.1)**	Hong Kong (13.3)	**Fiji (16.0)**
6	Rep. of Korea (2.4)	**Samoa (21.4)**	India (8.0)	Japan (23.9)
7	Myanmar (1.2)	**New Caledonia (20.7)**	Bangladesh (3.9)	Philippines (23.9)
8	Viet Nam (0.8)	**Vanuatu (18.3)**	North Mariana Isls (1.5)	**New Caledonia (22.4)**
9	Hong Kong (0.4)	**Tonga (18.1)**	Australia (0.8)	**Samoa (19.2)**
10	Pakistan (0.3)	**Cook Islands (10.5)**	New Caledonia (0.7)	**Tonga (17.4)**

Source: ESCAP and UNISDR (2010) using the EM-DAT database.

Table 29-5: Climate migration options in the Pacific.

	Type of mobility	
	Induced	**Forced**
Migration	**Individuals and families migrate**	**Communities relocate**
Internal		
- Proximate (own lands)	Not likely	Least disruptive
- Proximate (others lands)	Not likely	Land can be problematic
- Distant (mostly urban-rural)	Most likely	Difficult to sustain community
External		
- Regional (other Pacific Island countries)	Possible	Possible to sustain community and lifestyle but land problematic
- International	Most likely	Very unlikely to sustain community and lifestyle

Source: Campbell (2010: 34).

Table 29-6: Economic structure of small islands and areas of potential emissions reduction.

Type of economy	*Sectors with significant emissions reduction potential*						
	Energy supply	Transport	Buildings (commercial /residential)	Industry	Agriculture	Forestry	Waste management and sewage
Aid dependent	X	X	X	X	?	?	X
Services dependent	√	?	√	X	?	X	√
Natural resource exporting	?	X	√	?	√	√	?
Diversified with manufacturing	√	?	√	√	?	?	?

Notes:
X = low potential for emissions reduction due to excessive cost or limited effectiveness
? = possible area for emissions reduction, although may depend on capacities within the islands
√ = rich area for exploring emissions reduction

Island Typology

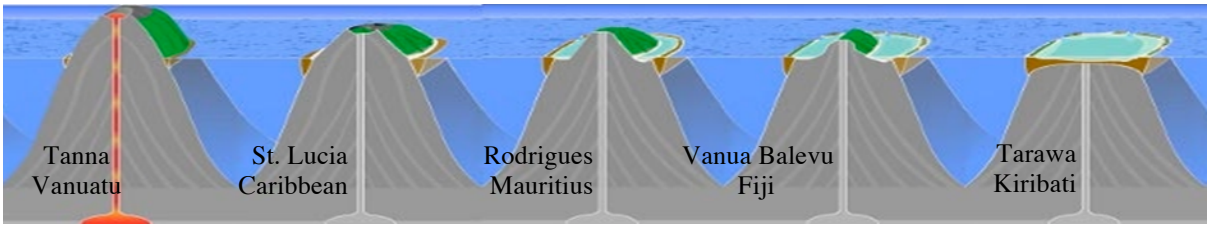


Figure 29-1: This schematic describes common tropical island typology from young high volcanic islands (left) through to atolls (submerged volcanics) on the far right. This simple overview highlights important components such as elevation and differing land and marine resources as well as the presence of coral reefs. On both high and low islands coastal settlement patterns predominate. Elevated limestone islands and islands comprised of 'continental' rocks are not included in this figure, but see Table 29-3.

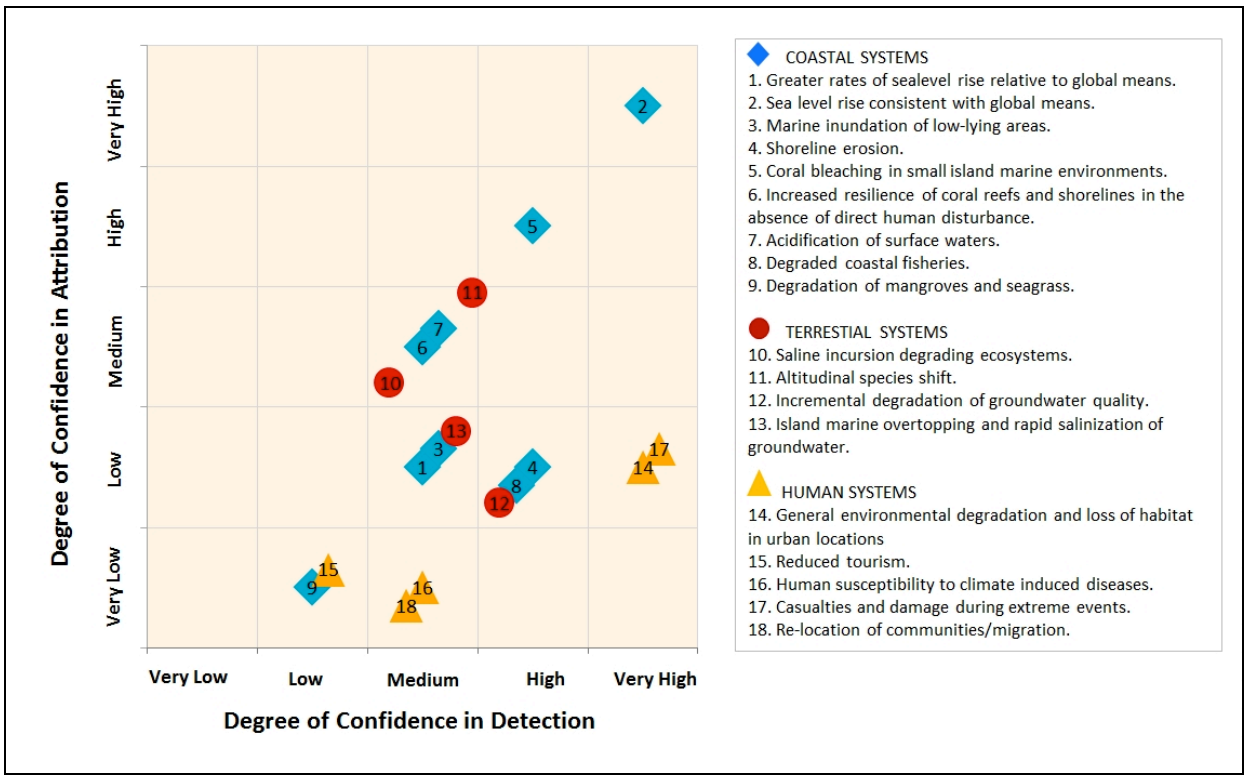


Figure 29-2: Based on available literature discussed in this chapter, the diagram shows a comparison of the degree of confidence in the detection of tropical small island impacts (horizontal axis) with the degree of confidence in attribution to climate change drivers (vertical axis). For example; the blue symbol No. 2 (Coastal Systems), indicates there is very high confidence in both the detection of "sea-level rise consistent with global means" and its attribution to climate change drivers; whereas the yellow symbol No. 17 (Human Systems) indicates whilst detection of "casualties and damage during extreme events" is very high, at this time there is low confidence in the attribution to climate change drivers. It is important to note that low confidence in attribution frequently arises due to the very limited research available for small island environments.

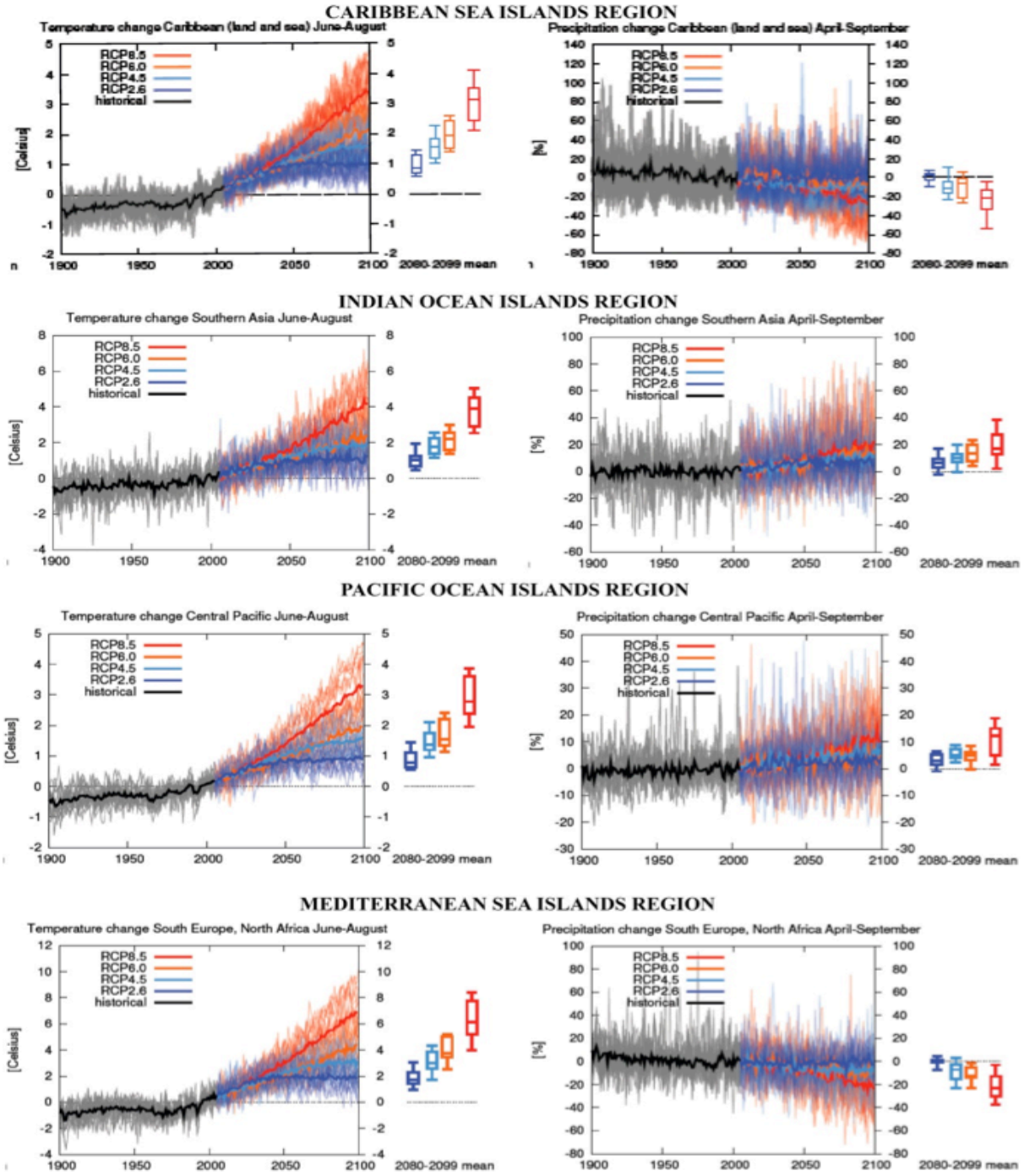


Figure 29-3: RCP Scenario projections to the year 2100 for the four main small island regions (adapted from AR5 WG1, Annex 1).

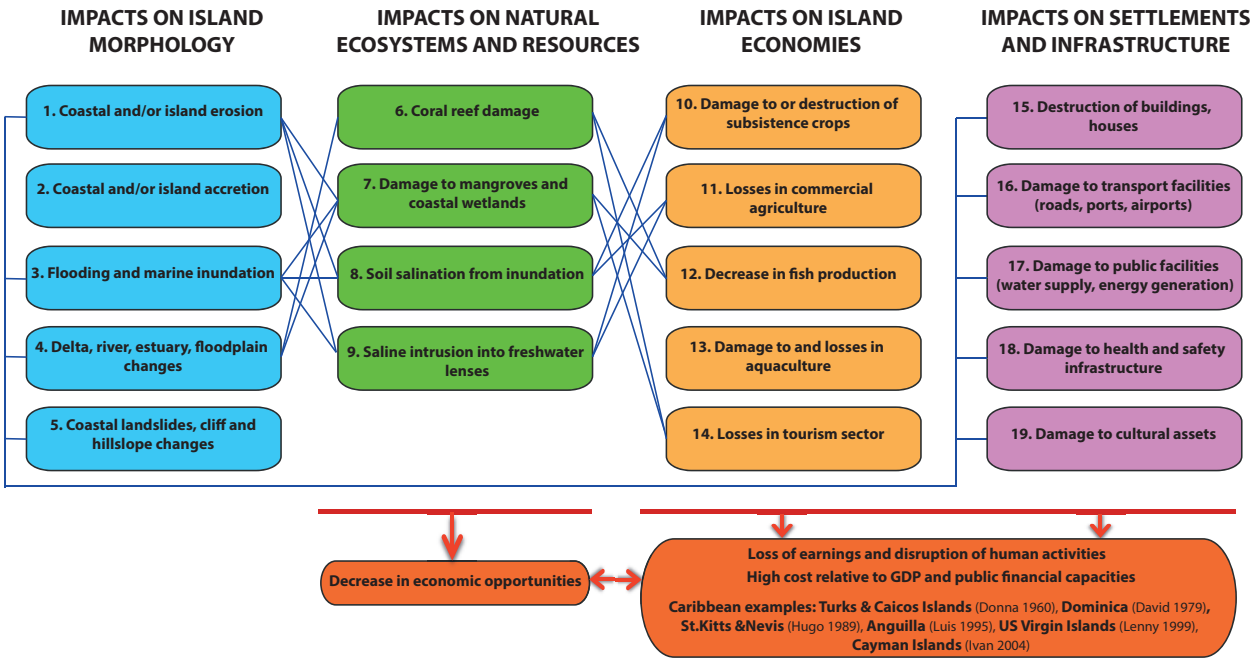
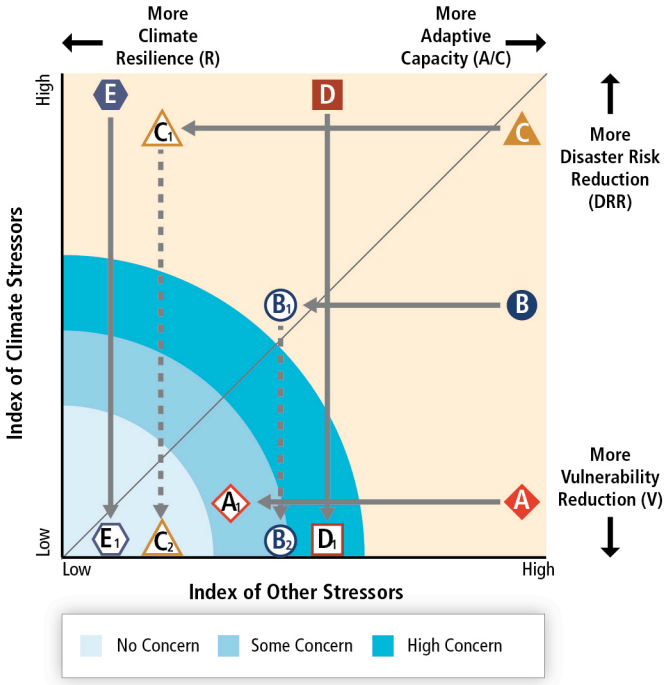


Figure 29-4: Tropical and extra-tropical cyclone impacts on the coasts of small islands: a. Example of tropical cyclone impacts on small island coasts with reference; b. Example of extra-tropical cyclone (mid-high-latitude lows) impacts on small island coasts with reference.

1a. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 1b. Maldives, April 1987 (Harangozo, 1992); 2a.Taveuni (Fiji) March 2010 (Etienne and Terry, 2012); 2b. Funafuti atoll, Tuvalu, October 1972 (Baines *et al.*,1974); 3a. Society and Autrales Islands, French Polynesia, February 2010 (Etienne, 2012); 3b.Maldives, April 1987 (Harangozo, 1992); 4a. Viti Levu, Fiji, March 1997 (Terry, *et al.,* 2002); 5a.Society Islands, French Polynesia, February 2010 (Etienne, 2012); 6a. Curacao, Bonaire, Netherlands Antilles, November 1999 (Scheffers and Scheffers, 2006); Hawaiian Islands (Fletcher *et al.,*, 2008); 8a. Marshall Islands, June 1905 (Spennemann, 1996); 9a. Pukapuka atoll, Cook Islands 2005 (Terry and Falkland, 2010); 9b. Solomon Islands, December 2008 (Hoeke, submitted); 10a. Vanuatu 2004 (Richmond and Savacool, 2012); 10b. Chuck, Pohnpei, Kosrae, Federated States of Micronesia, December 2008 (Hoeke, submitted); 11a. 12a. 13a. Tuamotu Islands, French Polynesia, 1982-83 (Dupon, 1987); 15a. Tubuai (Australes Islands) February 2010 (Etienne, 2012); 15b. Majuro, Marshall Islands, November 1979 (Hoeke, submitted); 16a. Vanuata February 2004 (Richmond and Savacool, 2012);16b. Coral Coast, Viti Levu, Fiji, May 2011 (Hoeke, submitted); 17a. Bora Bora,Raiatea, Maupiti, Tahaa, Hahine (Society Islands) February 2010 (Etienne, 2012);17b. Majuro, Kwajalein, Arno Marshall Islands,December 2008 (Hoeke, submitted); 18a. Vanuatu, February 2004 (Richmond and Savacool, 2012); 18b. Bismark Archiplago, Papua New Guinea, December 2008 (Hoeke, submitted); 19a. Tuamotu (French Polynesia) 1982-83 (Dupon, 1987).



	Policy Focus		Additional Policy Objective	
A	Reducing vulnerability to non-climate stressors	A_1		
B	Reducing vulnerability to non-climate stressors AND disaster risk reduction	B_1	Creating climate resilience	B_2
C	Reducing vulnerability to non-climate stressors AND disaster risk reduction	C_1	Climate resilience	C_2
D	Disaster risk reduction AND climate resilience	D_1		
E	Climate resilience	E_1		

Figure 29-5. Potential benefits and risks associated with alternative climate change adaptation actions or policies.

Chapter 30. The Ocean

Coordinating Lead Authors
Ove Hoegh-Guldberg (Australia), Rongshuo Cai (China)

Lead Authors
Peter G. Brewer (USA), Victoria J. Fabry (USA), Karim Hilmi (Morocco), Sukgeun Jung (Republic of Korea), Elvira Poloczanska (Australia), Svein Sundby (Norway)

Contributing Authors
William Skirving (USA/Australia), Michael Burrows (UK), Johann Bell (Fiji), Long Cao (USA), Simon Donner (Canada), C. Mark Eakin (USA), Arne Eide (Norway), Ben Halpern (USA), Chuck McClain (USA), Mary O'Connor (Canada), Camille Parmesan (USA), Ian Perry (Canada), Anthony J. Richardson (Australia), Christopher J. Brown (Australia), David Schoeman (Australia), Sergio Signorini (USA), Siri Strandenes (Norway), William Sydeman (USA), Rui Zhang (China), Ruben van Hooidonk (USA), Skip McKinnell (Canada), Daithi Stone (USA)

Reviewing Editors
Carol Turley (UK), Ly Omar (Senegal)

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Executive Summary

The Ocean plays a central role in Earth's climate, absorbing over 90% of the heat added to the global climate system through the enhanced greenhouse effect. [WGI 3.2] The Ocean is also a major sink for anthropogenic CO_2 emissions. [WGI Box 3.2] Here, we assess the evidence for changes due to anthropogenic climate change (including acidification from rising atmospheric CO_2) on the Ocean as a region. It is *virtually certain* that anthropogenic climate change is already changing ocean temperature and acidity, as well as ocean productivity, trophic structure, and the distribution of species and ecosystems. The world's Ocean, however, encompasses a large variety of oceanographic and ecosystem structures and functions, and, hence, a wide variety of regional responses to climate change. We address this diversity by dividing the Ocean into eight sub-regions: High Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), Coastal Boundary Systems (CBS), Equatorial Upwelling (EUS), Subtropical Gyres (STG), Semi-Enclosed Seas (SES), the Deep Sea (DS, >1,000 m), and Polar Seas. Dividing the Ocean into these sub-regions takes into account the diversity of marine environments and ecosystems at a large-scale although we acknowledge that any attempt is unlikely to be universally acceptable given the many bases by which this might be done (e.g. ecosystem, biogeochemical). Polar Seas (defined by the presence of sea ice) are not considered here as they are dealt with in Chapter 28. Our assessment reveals widespread impacts on organisms and ecosystems arising from the fundamental changes that have occurred within the physical and chemical conditions of the Ocean (*very high confidence*). Clear attribution of these changes to climate change depends on the sub-region and the physical, chemical or biological components involved. We discuss the implications of observed changes for different ocean sectors and sub-regions as climate change occurs.

The physical and chemical properties of the Ocean have changed significantly over the past 60 years (*very high confidence)*. Heat content has increased in the upper layers of the Ocean since 1950 consistent with the positive radiative imbalance of the climate system driven by anthropogenic greenhouse gas emissions. Temperatures in many sub-regions have been influenced by long-term variability (e.g. Pacific Decadal Oscillation, PDO, Atlantic Multidecadal Oscillation, AMO) as well as anthropogenic climate change, with the effects of variability being heightened at regional scales. Regional changes have also occurred in wind speed, surface salinity, ocean currents, solar irradiance, cloud distribution, and oxygen depth profile (*robust evidence, high agreement)*. Thermal expansion and melt water from glaciers and ice-caps have increased sea levels globally and to different extents regionally (*virtually certain)*. Surface warming of the Ocean and changes in wind speed have also increased the thermal stratification of the upper ocean in some regions (*high confidence*). Increased uptake of atmospheric carbon dioxide by the Ocean has decreased ocean pH and fundamentally changed the carbon chemistry of the Ocean *(very high confidence)*. The present state and rate of change of combined ocean pH and the concentration of carbonate ions are unprecedented in millions of years (*robust evidence, high agreement*). [30.3.1, 30.3.2; 6.1.1, 6.2.2.1; WGI 3.2 – 3.8, 10.41-10.4.4]

The Ocean is *virtually certain* to continue to warm and acidify as emissions continue to increase although differences between Representative Concentration Pathways (RCP) are likely to be minimal until 2035 (*high confidence, $p \leq 0.01$*). Projected temperatures of the surface layers of the ocean, however, diverge as the 21st century unfolds and will be 1-3°C higher by 2100 under RCP8.5 than RCP2.6 across most ocean sub-regions. Projected warming beyond 2100, however, is *very likely* to eventually reach average global temperatures and hence ocean temperatures that are 3-11°C above today. Ocean chemistry (pH, carbonate concentrations, and oxygen concentrations) is *virtually certain* to continue changing, with conditions approaching those not seen for 40 million years if atmospheric CO_2 continues to increase in the atmosphere (*very high confidence*). Based on the substantial response of ocean systems to the relatively small amounts of change so far, projected changes in atmospheric greenhouse gas concentrations and temperature are *virtually certain* to drive fundamental and far-reaching changes to the structure and function of ocean ecosystems (*high confidence*), and consequently the goods and services they provide for humanity (*medium confidence*). [30.3.1, 30.3.2, 6.3, 6.4; WGI 3.2, 3.8; Box 3.2, 12.4.7.1, 12.5]

Changes to ocean conditions have resulted in fundamental and extensive changes to organisms and ecosystems in the Ocean. Marine organisms are moving to higher latitudes consistent with warming trends (*high confidence*). Isotherms are migrating rapidly (10-20 km yr^{-1}) across the ocean surface in some regions, especially at lower latitudes causing marine organisms to move, acclimatise, or adapt evolutionarily. The greatest rates of movement of organisms to higher latitudes are seen amongst mobile organisms such as fish, crustaceans and

zooplankton assemblages, especially at higher latitudes *(robust evidence, high agreement)*. These changes have also been influenced by diverse factors such as the loss of sea ice, transcontinental shipping and the alteration of coastlines by rising sea levels (*medium evidence, medium agreement*). Increased sea temperatures have also significantly altered the phenology or timing of key life-history events such as plankton blooms, migratory patterns, and spawning in fish and invertebrates over recent decades (*medium confidence*). [30.4, 30.5; 6.2, 6.3, 6.5]

Ocean acidification resulting from the increased flux of atmospheric CO_2 into the Ocean represents a fundamental challenge to marine organisms and ecosystems, although the extent of its influence varies with the taxa and process involved (*high confidence*). The sensitivity of organisms to ocean acidification is highest in the earliest life history stages (*high confidence*). While there is *robust evidence*, *high agreement* and *high confidence* from controlled laboratory experiments and mesocosm studies that ocean acidification significantly impacts a large range of organisms (e.g. corals, fish, pteropods, coccolithophores, and macroalgae), physiological (e.g. skeleton formation, gas exchange, reproduction, growth and neural function) and ecosystem processes (e.g. productivity, reef building and erosion), there are fewer field studies that have shown (or not shown) direct ecosystem changes. Our understanding of synergies and interactions of increased ocean acidification with increased sea temperature is also limited and should be a priority of future studies. [30.3.1, 30.3.2, 30.4, Box CC-OA, 6.2, 6.3, 6.5, Box 5.1, 6.2]

Climate change, by increasing temperatures and altering surface winds, has influenced ocean mixing, nutrient levels and primary productivity. These changes are very likely to have positive consequences for some fisheries and negative ones for others through the de-oxygenation of deep water environment and associated spread of hypoxic zones (*medium evidence, medium agreement).* Changing surface winds have produced major changes in the supply of nutrients to the upper layers of the ocean. In regions where primary production has increased (or is predicted to increase), such as in the High Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), and Equatorial Upwelling (EUS), energy transfer to higher trophic levels is *likely* to increase along with microbial activity. Increased primary productivity is *likely* to lead to an increased transfer of organic carbon to deep sea habitats stimulating respiration and drawing down oxygen levels in some areas. These changes are further influenced by the contribution of nutrients from coastal pollution, leading to the expansion of hypoxic (low in oxygen) zones in areas such as the Gulf of Mexico, North Sea, Arabian Sea, and coastal areas of many countries. Increasing temperatures will also reduce the solubility of oxygen, adding to oxygen stress (*very high confidence*). [30.5.2, 30.5.4, 30.5.6; 6.2, 6.3, 6.5]

Chlorophyll concentrations have decreased in the STGs in the North Pacific, Indian and North Atlantic Oceans by 9%, 12% and 11%, over and above the inherent seasonal and interannual variability from 1998 to 2010 (*high confidence; $p<0.05$*). Significant warming over this period has resulted in increased water column stratification and reduced mixed layer depth. This has reduced the vertical transport of nutrients into the upper layers of the Ocean and has reduced primary production by phytoplankton in these vast areas (as measured by chlorophyll, see 6.3.1 for associated uncertainties). Reducing primary production is *likely* to impact food availability for pelagic fish species (*limited evidence, medium agreement*). The influence of long-term variability complicates attribution of past changes directly to climate change. Changes in ocean primary productivity, chlorophyll, and other key biogeochemical processes are complex and our understanding how they are likely to change with climate warming is *limited*. [30.5.5.1, Table 30-2, 6.3, 6.1.3, 6.5]

Increasing ocean temperatures are driving a greater frequency of elevated temperature events that have had significant impacts on coastal ecosystems (*very high confidence*). In some cases (e.g. coral reefs, Mediterranean intertidal communities), the projected degradation of these marine ecosystems is *very likely* to pose substantial challenges for coastal societies where livelihood and food security may depend on ecosystem health. Many coastal ecosystems, however, are also affected by a wide range of non-climate change related human activities, making clear attribution of observed changes to climate change difficult. Reducing regional stressors represents an opportunity to strengthen the ecological resilience of these ecosystems which may help them survive projected changes in ocean temperature and chemistry. [30.4, 30.5.3; 30.5.6, 6.2.2.4, 6.3.2, 6.5.2; Box CC-CR]

High Latitude Spring Bloom systems (HLSBS) in the North Eastern Atlantic are changing in response to warming oceans (*high agreement, medium evidence).* These ecosystems are responding to rapid warming, with the greatest changes being observed since the late 1970s in the phenology, distribution and abundance of plankton

assemblages, and the reorganisation of fish assemblages. For example, the abundance of boreal species has decreased along the southern fringe and increased along the northern fringe of the HLSBS since cool phase of Atlantic Multidecadal Oscillation (AMO) in the 1960s and early 1970s. However, substantial natural variability over the past 30 years is embedded in the entire Northeast Atlantic region as part of the AMO (WG1 Chapter 14). These changes have both positive and negative implications for the future of the fisheries within the HLSBS. [30.5.1, 30.8.3]

The world's Semi-Enclosed Seas have been changing rapidly since 1982 with projected changes having important ramifications for surrounding countries (*medium confidence*). The upper layers of the world's Semi-Enclosed Seas (SES) show significant warming since 1982, although this warming signal is strongly influenced by long-term variability (e.g. AMO). Further warming is projected which is *very likely* to expose the SES to greater thermal stratification, which will lead *very likely* to reduced oxygen levels at depth and the spread of hypoxic zones, especially in the Baltic and Black Seas. These changes are *likely* to impact regional ecosystems as well as fisheries, tourism, and other human activities although the understanding of the potential impacts is relatively undeveloped. [30.3, 30.5.6]

Evidence that the world's most abundant habitat, the deep sea, is changing is compelling but requires further research (*medium agreement, limited evidence*). Deep sea habitats (>1000 m) occupy 60% of the planet's surface yet are little understood due to the difficulties of accessing them. Deep water coral communities are vulnerable to changes in ocean pH and carbonate chemistry. There is *medium evidence and agreement* that an increased nutrient supply through intensified upwelling in some regions (through intensified upwelling) threatens deep sea ecosystems with hypoxia by increasing the rate of metabolism (and hence oxygen use). Similarly, a decrease in primary productivity in some areas (e.g. subtropical gyres) may reduce the availability of organic carbon to deep sea ecosystems. These changes are *virtually certain* to increase due to the amplifying influence of rising deep water temperatures on microbial metabolism. Our understanding, however, of the changes in deep sea habitats that are currently occurring, and will occur, is limited. [30.5.7, 6.1.1.2, 6.1.1.3]

The observed and projected impacts on ocean ecosystems and processes reveal significant regional differences that will require differing policy responses and adaptation approaches (*medium agreement, medium evidence*). Changes to the distribution and abundance of fish species as waters warm and acidify will dictate the need for flexible and informed decision-making. For example, tuna, a key fisheries species, are highly sensitive to changes in sea temperature and changes in their distribution and abundance will provoke new technological and policy challenges. The cross-boundary migration of fish stocks (from the waters of one nation to another) will require international cooperation and evidence-based decision making. [30.5.5.2, 30.6.3]

Projected change to ocean ecosystems as a result of ocean warming and acidification will reduce access to food, and increase poverty and disease in many countries (*medium agreement, limited evidence*). Key fisheries throughout the world are being impacted by climate change, through direct physiological and ecological impacts. In many parts of the world (particularly in the tropical and subtropical regions), fisheries are in decline and will continue to do so under rapid anthropogenic climate change. Reduced access to food in some coastal regions as a result of declining fisheries will expose greater numbers of already vulnerable people to reduced access to food and will result in associated health impacts. Disease, impacts of harmful algal blooms, cholera, and ciguatera poisoning are also *likely* to increase as oceans warm and acidify. Understanding of these changes and their origin is important although limited. [30.6.3, 30.6.5]

Building dynamic fisheries management as well as sustainable aquaculture represent opportunities for adaptation to changes in the distribution and productivity of fish stocks (*high agreement, medium evidence*). The application of ecosystem-based management which includes climate change to manage the development and maintenance of fish stocks represents a key tool for adapting to changes resulting from climate change. Reducing non-sustainable fishing (e.g. bottom trawling, 'ghost' fishing) provides an avenue for adapting to climate impacts by reducing the impact of additional stressors. Changes to coastal fishing due to the loss of coastal ecosystems will require adaptation strategies such as marine protected areas, alternative livelihoods and/or the movement of people and industry sectors. Industries such as nature-based tourism will require similar strategies for decision-making. [30.6.3, 6.5, Ch7]

Changes to surface winds, sea level, wave height and storm intensity will increase the risks associated with coastal and ocean-based industries such as shipping, oil, gas and mineral extraction (*medium agreement, medium evidence*). Storm impacts on coastal areas will increase with sea level rise through greater storm surge impacts. [WGI, 3.7.4] Strategies will require consideration of these changes in the design and use of ocean-based infrastructure together with the evolution of policy for reducing risks to equipment and people. New opportunities for shipping, oil, gas and mineral extraction, as well as international issues over access and vulnerability, are likely to evolve as waters warm, particular in high latitude regions. [30.6, 6.5]

Adapting to the impacts of climate change within the Ocean is poorly developed but will benefit from improved forecasting and early warning systems (*medium agreement, limited evidence*). Given the reduced opportunity to mitigate ocean warming and acidification directly due to the scale of the problem, adapting fisheries strategies based on forecasting as well as developing ecosystem-based management strategies for fish stocks will help sustain many fisheries under climate change to some extent. Similarly, advanced warning systems can be used to help modify aquaculture management such as treating inflowing water to facilities during periods of low pH. While some examples exist of adaptation along these lines, the options are poorly developed for the broader set of impacts from climate change. [30.6]

Ocean ecosystems and associated sub-regions offer a large potential for carbon dioxide mitigation strategies (*medium agreement, limited evidence*). Ecosystems such as mangroves, seagrass and salt marsh represent potentially significant carbon sequestration strategies (e.g. 'blue carbon'). Reducing highly anoxic habitats through coastal restoration (and hence the emission of methane) also represent significant mitigation opportunities, although an understanding of these opportunities is limited. [30.7] There are also significant opportunities for ocean-based industries such as international shipping to continue to reduce their emissions intensity, as well as projects that source offshore wind and tidal power. Sequestration of anthropogenic CO_2 into deep ocean areas has been explored although studies indicate significant hurdles with respect to the expense and vulnerability of deep water marine ecosystems.

International frameworks for decision-making and collaboration represent vital tools for anticipating and responding to impacts of global climate change (including ocean acidification) on marine systems. UNCLOS, LOSC and other international frameworks provide the common basis for countries to recognise the common challenges arising from the impact of climate change on the ocean and to solve problems as diverse as creating sustainable fisheries across national borders, collaborative responses to the impacts of extreme events, and strengthening international food security through sustainable marine resources. Given the importance of the ocean to all countries, there is a need for the international community to progress rapidly to 'whole of ocean' strategies for responding to the challenges associated with anthropogenic climate change.

30.1. Introduction

The Ocean exerts a profound influence on the Earth, interacting with its atmosphere, cryosphere, land and biosphere to determine planetary conditions. It also directly influences human welfare through the provision and transport of food and resources, as well as cultural and economic benefits, and indirectly through the regulation of atmospheric gas content and distribution of heat and water across the planet. The present chapter evaluates the current impacts and future implications for Ocean sub-regions of increased concentrations of atmospheric greenhouse gases and other anthropogenic alterations to planetary radiative forcing. We also include the influence of changes to the chemistry of the Ocean through its acidification by increasing atmospheric carbon dioxide concentrations. In doing so, this chapter assesses recent scientific evidence and examines the extent to which significant changes can be accurately detected and attributed to anthropogenic climate change. The impacts, risks and vulnerabilities associated with climate change are assessed within seven ocean sub-regions, and the impacts and adaptation options for key ocean-based sectors discussed. Polar oceans are not directly considered here as they are given detailed treatment elsewhere (WGII Ch28). It is also noteworthy that while the impact of climate change on ocean sub-regions directly influences the coastal and low-lying sub-regions of multiple nations, a detailed discussion of these potential impacts also occurs in the relevant chapters of this report (e.g. WGII Ch5, Ch29).

30.1.1. Major Sub-Regions within the Ocean

The Ocean represents a vast region which stretches from the high tide mark to the deepest oceanic trench (11,030 m), and occupies 71% of the earth's surface. There are considerable challenges in assessing the regional impacts of climate change on the Ocean. Not only is the Ocean vast but it also contains a very broad diversity of life forms and habitats, many of which are poorly documented and not easily studied due to the difficulty of visiting much of this enormous region. Devising an appropriate structure in order to explore the influence of climate change on the entire ocean system is consequently challenging. *Longhurst* [1998] identified over 50 distinct ecological provinces in the ocean, defined by physical forcing, and the structure and function of phytoplankton communities. Longhurst's scheme, however, yields far more sub-regions than could be sensibly discussed in the space allocated here. Consequently, we have used comparable principles but have divided the non-polar ocean into seven larger sub-regions similar to *Barber* [1988]. In this case, our sub-regions are unified by specific physical forcing and ecosystem structure that might be expected to respond to climate change in broadly distinct ways (Figure 30-1, Table 30-1). We recognize that these sub-regions do not always map perfectly over physical-chemical patterns or specific geographies, and that they interact with strongly with terrestrial regions through weather systems and the exchange of materials. We also recognize that different ocean sub-regions may have substantially different primary and fishery productivities. Notably, over 80% of fisheries production is associated with three ocean sub-regions Northern hemisphere High Latitude Spring-bloom (HLSBS), Coastal Boundary Systems (CBS), and Eastern Boundary Upwelling Ecosystems (EBUE; Table 30-1, Figure 30-1B). The Deep Sea (>1,000m) is included as separate category which overlaps the six other ocean sub-regions.

[INSERT FIGURE 30-1 HERE
Figure 30-1: A. The world's non-polar oceans have been separated into seven major sub-regions, with polar oceans being excluded due to treatment elsewhere (Ch28). The chlorophyll concentration averaged over the period from Sep 1997 – 30 Nov 2010 (NASA) is also shown. Together with key oceanographic features, primary production was the basis for separating the ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). Numbers refer to: 1 = High Latitude Spring Bloom Systems (HLSBS), 2 = Equatorial Upwelling (EUS), 3 = Semi-enclosed seas (SES), 4 = Coastal Boundary Systems (CBS), 5 = Eastern Boundary Upwelling Ecosystems (EBUE), 6 = Subtropical gyres (STG), and 7 = Deep sea (>1000 m). B. relationship between fish catch and areas for Ocean sub-regions shown in A. Red columns: average fish catch (millions tons yr^{-1}) for the period 1970-2006. Blue columns: area (millions km^2).]

[INSERT TABLE 30-1 HERE
Table 30-1: Percent area of the ocean, primary productivity and fisheries catch (production) for major sub-regions of the ocean (for location of sub-regions, see Figure 30-1).]

30.1.2. Detection and Attribution of Climate Change within the Ocean

The primary goals of Chapter 30 were to assess recent literature with respect to the detection and attribution of climate change to the physical, chemical and biological components of the Ocean and its sub-regions. Within Chapter 3 of IPCC AR5 from Working Group I (WGI), detailed observations of changes to the physical and chemical characteristics of the Ocean are described, while Chapter 10 assesses the influence of anthropogenic climate change on ocean heat content, ocean salinity on freshwater fluxes, sea level, and oxygen (WG1 10.4). These observations are assessed relative to near and long-term projections generated by CMIP5 models (WGI Chapters 11-12). We extend assessment to the observed changes in the physical and chemical characteristics of the Ocean in response to anthropogenic climate change by assessing change on Ocean sub-regions.

Attribution follows the detection of a change by addressing the question as to whether climate change has significantly contributed to the observed change [18.2.1.1]. We attempt to do this for a wide range of changes within our defined sub-regions within the Ocean. There are a number of general limitations to the detection and attribution of impacts to climate change (including ocean acidification) that are discussed elsewhere [18.2.1.2]. Challenges with

respect to ocean temperature and heat content, acidification, salinity, sea level, and oxygen are dealt with in Chapter 10 (WGI). Generally, attribution to climate change occurs when the full range of possible forcing factors is considered and those related to climate change are found to be the most likely explanation for the change in question. Comparing detected changes to the expectations of well-established scientific evidence plays a central role in the successful attribution of detected changes. Approaches and 'best practice' guidelines are discussed in Chapters 10 and 18 (WGI), as well as several other places [*Hegerl et al.*, 2010; *Hegerl and Zwiers*, 2007; *Stott et al.*, 2010].

Achieving successful detection and attribution of recent changes in ocean systems is complicated, as is the case on land, by the influence of sources of long-term and complex variability such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). The fragmentary nature of ocean observing, uncertainty of model simulations, and confounding influences of anthropogenic factors unrelated to climate change represent significant challenges [*Hoegh-Guldberg et al.*, 2011a; *Parmesan et al.*, 2011]. Anthropogenic climate change (e.g. ocean warming and acidification) are co-mingled with other human driven changes (e.g. pollution, introduced species, overexploitation of fisheries, and disease, [*Halpern et al.*, 2008] thereby frustrating efforts to establish a clear climate change signal. Long-term records are essential for this task but are rare, especially in difficult to access oceanic environments. Stressors not related to climate change may also interact synergistically or antagonistically with each other and climate change, further vexing the process [*Hegerl et al.*, 2010; *Hegerl and Zwiers*, 2007].

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change on the Ocean as a region was not done during previous IPCC assessment reports, although a chapter devoted to the Ocean in the Second Assessment Report (SAR) did "attempt to assess the impacts of projected regional and global climate changes on the oceans" [*Ittekkot et al.*, 1996]. Notwithstanding, attempts to detect and attribute the impact of climate change on observed changes in ocean and coastal systems are spread throughout previous assessment reports, reducing an key opportunity to synthesize the physical, chemical and biological changes and their causes within the Ocean and its sub-regions. The IPCC Fourth Assessment Report (AR4) concluded, however, that while terrestrial sub-regions are warming faster than the oceans, "Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000 m and that the ocean has been taking up over 80% of the heat being added to the climate system." AR4 also concluded that sea levels had risen due to the thermal expansion of the ocean but recognized that our understanding of the dynamics of glaciers and ice sheets was "too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise" (AR4 SPM).

Changes to ocean temperature and density also have the potential to alter large-scale ocean circulation. AR4 concluded, however, with respect to the Meridional Overturning Circulation (MOC) that "it is very likely that up to the end of the 20th century the MOC was changing significantly at interannual to decadal time scales" (AR4 WGI, CH5, Box 5.1), although definitive evidence of a slowing MOC was lacking. According to AR4, "sea-level rise over the last 100 to 150 years is probably contributing to coastal erosion in many places" including the east coasts of the United States and United Kingdom (AR4, WGII Chapter 1). The AR4 assessment was *virtually certain* (Table 7.3), however, that rising atmospheric CO_2 had changed ocean chemistry (buffering, carbonate), and that a decrease in surface pH of 0.1 had occurred over the global ocean, which was calculated from the uptake of anthropogenic carbon estimated to have occurred between 1750 and 1994 [*Raven et al.*, 2005; *Sabine et al.*, 2004] ; AR4, 5.4.2.3].

Large-scale changes to ocean salinity were also observed from 1955 to 1998, which were "characterised by a global freshening in sub-polar latitudes and salinification of shallower parts of the tropical and subtropical oceans" (AR4 WGI Chapter 5). In this case, freshening was observed in the Pacific, with increased salinity being observed in the Atlantic and Indian Oceans (AR4, WGI, and ES). These changes in surface salinity were qualitatively consistent with observed and expected changes to surface freshwater flux. Freshening of mid- and high-latitude waters together with increased salinity at low latitudes were seen as evidence "of changes in precipitation and evaporation over the oceans".

Substantial evidence indicated that changing ocean conditions have extensively influenced marine ecosystems (AR4, WGI, Table 1.4). The abundance and productivity of pelagic plankton assemblages have responded to regional changes in sea temperature, stratification, upwelling, iron deposition, and other physical and chemical changes [*Hayes et al*., 2001]. Changes in the distribution and timing of reproduction were also reported in a range of organisms, although a separate detection and attribution of changes to climate change (from terrestrial studies) was not done as part of AR4. AR4 noted that there is an "accumulating body of evidence to suggest that many marine ecosystems, including managed fisheries, are responding to changes in regional climate caused predominately by warming of air and sea surface temperatures (SSTs) and to a lesser extent by modification of precipitation regimes and wind patterns".

Observed changes in marine ecosystems and managed fisheries within AR4 included: changes to plankton community structure and productivity, pelagic phenology and biogeography, intertidal communities along rocky shores, kelp forests, and the distribution of pathogens and invasive species. Changes were also observed in coral reefs through increased mass coral bleaching and mortality, populations and biogeography, migratory patterns and trophic interactions of sea birds, marine reptiles and mammals, as well as a range of other marine organisms and ecosystems (AR4, WGII, Table 1.5).

30.3. Recent Changes and Projections of Ocean Conditions

Understanding the extent to which the physical and chemical environments of the Ocean and its sub-regions have changed is centrally important to the interpretation of how organisms and ecosystems are likely to change over the coming decades and century. Increasing concentrations of atmospheric CO_2 have increased average global temperature and subsequently the temperature of the Ocean, and have fundamentally altered its chemistry (AR5, WGI, Executive Summary). Expert archives such as HadISST1.1 contain sea surface temperature (SST) from a range of sources allowing an opportunity to explore monthly mean gridded, global SSTs from 1870 to present [*Rayner et al*., 2003]. The HadISST1.1 data set is used here to investigate regional trends in SST within six of the seven sub-regions (Table 30-1), along with a range of other expert data sets for other variables including sea level, wind speed, water movement, water column structure, oxygen concentration, biogeochemistry and salinity.

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

There is little disagreement that Ocean has been dominant sink for most (>90%) of the extra heat arising from the human influence on Earth's radiative balance (*virtually certain;* WGI Box 3.1). As a result, the upper layers of the Ocean (0-75 m) have warmed significantly (>0.1°C per decade) since global observations became available (*virtually certain*). The intensification of the warming signal is associated with an increased thermal stratification of the upper layers (0-200 m) of the Ocean of around 4% over a 40-year record. These changes have a significant (*virtually certain*, $p < 0.01$) anthropogenic signal [*Gleckler et al*., 2012]**.** Rates of warming decrease to 0.015°C per decade at 700 m and are likely to be small but positive at deeper depths (<0.01°C per decade; WGI 3.2.2, Figure 3.1). All three ocean basins are warming at rates that exceed that expected if there were no changes to greenhouse gas forcing over the past century (Figure 3.2).

We use published HadISST 1.1 to explore trends in historic SST with our sub-regions outlined in Figure 30-1. The .2median SSTs for 1871-1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the Met Office Marine Data Bank (MDB) to produce monthly globally-complete fields of SST on a 1º latitude-longitude SST grid from 1870 to date. The higher resolution HadISST 1.1 dataset (as compared to HadSST3) is best suited for use in this chapter.

The surface waters of the three ocean basins are warming similarly, with the Atlantic Ocean warming faster (0.3ºC decade^{-1}), than the Pacific (0.20ºC decade^{-1}) and Indian (0.11ºC decade^{-1}) Oceans (Figure 30-2). All but one of the Ocean sub-regions (exception being SES) have warmed significantly over the period 1950-2009 (HadISST1.1 data,

Table 30-2) although trends in temperature vary at a finer scale (e.g. South versus North Pacific, Table 30-2, Figure 30-3A). Notably, the southern portions of the HLSBS also did not show significant warming over this period although the northern hemisphere HLSBS did (Table 30-2). The rates of warming observed for the North Atlantic are consistent with the analysis of Advanced Very High Resolution Radiometer (AVHRR) satellite data combined with *in situ* measurements from ships and buoys collected in the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, icoads.noaa.gov)[*González-Taboada and Anadón*, 2012]. Among the Eastern Boundary Currents, the Canary and Californian currents exhibited significant warming (0.09°C.decade^{-1} and 0.12°C.decade^{-1} respectively; $p < 0.05$) while the Benguela and Humboldt currents did not show significant temperature changes ($p > 0.05$; Table 30-2). The Coastal Boundary Systems showed highly significant warming (from 0.09°C.decade^{-1} to 0.13°C.decade^{-1}, Table 30-2). All subtropical Gyres (except the North Atlantic sub-tropical gyre) exhibited significant warming although rates were lower than analyses done over shorter periods (e.g. 1998 to 2010 [*Signorini and McClain*, 2012] and based on NOAA_OI_SST_V2 data (Figure 30-12B). Trends from 1950-2009 were not significant within the five SES analyzed here, although studies done of shorter periods (e.g. 1982-2006, [*Belkin*, 2009] reveal significant increases in SST temperature of: Baltic (1.35°C), Black (0.96°C), Red (0.74°C) and Mediterranean (0.71°C) Seas. These more recent and shorter length studies are complicated by the influence of patterns of long-term variability, most probably influenced by their small and land-locked nature. Given the large sensitivity of coral reefs to temperature anomalies [*Eakin et al.*, 2010; *Strong et al.*, 2011], we also examined the temperature trends in key coral reef regions using the World Resources Institute's Reefs at Risk (www.wri.org) to identify HadISST1.1 grid cells containing coral reefs (Figure 30-4). Grouping the results into six major coral reef regions, we found that coral reef waters had increased in temperature over the 50 year period examined by 0.36-0.65°C (Table 30-2).

[INSERT FIGURE 30-2 HERE
Figure 30-2: Observed and simulated variations in past and projected future annual average sea surface temperature over various oceanic regions. The black line shows estimates from HadISST1 observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), the "RCP4.5" emissions scenario (62), and the "RCP8.5" (62). Data are anomalies from the 1986-2006 average of the HadISST1 data (for the HadISST1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

[INSERT FIGURE 30-3 HERE
Figure 30-3: Analysis of data from Hadley Centre (HadISST 1.1, [*Rayner et al.*, 2003]) for different ocean sub-regions. A. Rate of change in sea surface temperature over the past 30 years (°C. decade^{-1}). B. Velocity at which isotherms are moving (km.decade^{-1}) from 1960-2009. C. Shift in seasonal changes that drive natural history events (days.decade^{-1}) for April and D. for October. E.]

[INSERT FIGURE 30-4 HERE
Figure 30-4: Location of coral reef grid cells used in Tables 30.2 and 30.4 as well as in Figure 30-11. Each dot is centred over a 1x1 degree grid cell within which lies at least one coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk (http://www.wri.org). The six regions are as follows: Red – Western Pacific; Blue – Eastern Pacific Ocean; Green – Caribbean & Gulf of Mexico; Yellow – Western Indian Ocean; Magenta – Eastern Indian Ocean; and Cyan – Coral Triangle & SE Asia.]

[INSERT TABLE 30-2 HERE
Table 30-2: Regional changes in sea surface temperature (SST) over the past 50 years for ocean sub-regions specified in Figure 30-1. A linear regression was fitted to all 1x1 degree monthly SST data extracted from the HadISST 1.1 data set (Rayner et al., 2003) for the period of 1950 to 2009 for each ocean sub-region. The Table includes the slope of the regression (ºC.decade^{-1}), p value of the slope being different to zero, Linear Change Over 50 Years (slope of linear regression multiplied by 5 to obtain the average change over 50 years, and the difference between the mean temperature (1950-1959) from the mean temperature 50 years later (2000-2009). The latter may be different to the linear change over 50 years if there is significant long-term variability around the trend line. The last column compares the linear trend with that calculated between the two means with significant deviations (<0.8 and > 1.2) shown in red. P values that exceed 0.05 are also shown in red.]

Burrows et al. [2011] examined the rate at which isotherms are migrating by calculating the ratio of the rate of temperature change (°C.year^{-1}) to the spatial gradient of temperature (°C.km^{-1}) over the period 1960-2009. Given the essential role that temperature plays in the biology and ecology of marine organisms [*Poloczanska et al.*, 2013; *Pörtner*, 2002], the speed of isotherm migration ultimately determines the speed at which populations must either move, adapt, or acclimatize to changing sea temperatures [*Burrows et al.*, 2011; *Hoegh-Guldberg*, 2012b; *Pörtner*, 2002]. This analysis and others (e.g. North Atlantic, *González-Taboada and Anadón* [2012]) reveals that isotherms are moving at high velocities (up to 20 km.yr^{-1}) across the ocean, especially at lower latitudes (Figure 30-3B; *high confidence*). Other sub-regions showed lower velocities with contracting isotherms (cooling) in some areas (e.g. the Central and North Pacific, and Atlantic, Oceans Figure 30-3B). There are also changes in the timing of seasonal temperature in both spring and fall/autumn (Figure 30-3 C, D). The timing of spring conditions has advanced by 2-5 day.decade^{-1} in many parts of the global ocean, although the extent of change varies geographically. These changes in thermal environments are likely to have impacts on a range of different biological processes including the migration of species to higher latitudes and the timing and synchrony of reproductive and other seasonal behaviors [*Burrows et al.*, 2011; *Poloczanska et al.*, 2013], although it is noteworthy that other variables (e.g. light, food, habitat) can play significant roles in determining the distribution and abundance of marine organisms.

Significant excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) have significant impacts on marine organisms and ecosystems [*Bensoussan et al.*, 2010; *Crisci et al.*, 2011; *Harley*, 2011; *Hoegh-Guldberg*, 1999]. Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly has proven useful in understanding recent changes to organisms and ecosystems [*Strong et al.*, 2011]. The total heat stress accumulated over the period 1981-2010 was calculated using the methodology of [*Donner et al.*, 2007] and a reference climatology based on 1985-2000 in which the highest monthly SST was used to define the thermal threshold, above which accumulated thermal stress was calculated as 'exposure time multiplied by stress' or Degree Heating Months (DHM). Thermal stress was calculated as the running total of four consecutive months. While most sub-regions of the ocean experienced an accumulation of heat stress (relative to a climatology based on the period 1985-2000), equatorial and high latitude sub-regions in the Pacific and Atlantic oceans have the greatest levels of the accumulated heat stress (Figure 30-5A). There was also a higher proportion of years that had had at least one stress event (DHM > 1) in the last 30 years (1981-2010) than in the preceding 30 years (1951-1980; Figure 30-5B). In the last 30 years, most sub-regions that have coral reefs have experienced heat stress sufficient to cause mass coral bleaching [*Strong et al.*, 2011] events every 2-3 years.

[INSERT FIGURE 30-5 HERE
Figure 30-5: Recent changes in thermal stress calculating using HadISST 1.1 data. A monthly climatology was created by averaging the HadISST monthly SST values over the period 1985-2000 to create twelve averages, one for each month of the year. The Maximum Monthly Mean (MMM) climatology was then created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each SST value, but only allowing values to be recorded if they were greater than zero (Donner et al., 2007). Three measures of thermal stress change were then created: (A) Total thermal stress for the period 1981-2010, calculated by summing all monthly thermal anomalies for each grid cell. (B) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951-1980 and (C) 1981-2010.]

Projections of future sea temperature changes were examined using ensemble averages from AOGCM simulations available in the CMIP5 archive (Table 30-3) for the four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5; [*van Vuuren et al.*, 2011]). Ensemble averages for each RCP are based on simulations from 10 to 16 individual models (Table 30-3). Model hind-cast changes matched those observed for Ocean sub-regions for the period 1980-2009 (HadSST 1.1, Table 30-2, Figure 30-2), with the model ensemble slightly overestimating the extent of change across the different Ocean sub-regions (slope of observed/model = 0.81, $r^2 = 0.76$, $p < 0.001$). In this way, the absolute amount of change projected to occur in the ocean sub-regions was calculated for near-term (2010-2039) and long-term (2070-2099) periods (Table 30-4). In the near term (2010-2039), changes in the temperature projected for the surface layers of the ocean are largely indistinguishable between the different RCP pathways due to the similarity in forcing until 2035. By the end of the century, however, SSTs across the Ocean sub-

regions were 1-3°C higher under RCP8.5 than those projected to occur under RCP2.6 (Table 30-4). The implications of these projected changes on the structure and function of oceanic systems are discussed in later in this chapter.

[INSERT TABLE 30-3 HERE
Table 30-3: CMIP-5 models used to create the Chapter 30 RCP 2.6, 4.5, 6.0 and 8.5 SST ensembles.]

[INSERT TABLE 30-4 HERE
Table 30-4: Projected changes in sea surface temperature (SST, ºC) over the next 90 years for Ocean sub-regions (Figure 30-1) using model runs from the Coupled Model Intercomparison Project Phase 5 (CMIP-5, http://cmip-pcmdi.llnl.gov/cmip5/). Runs were divided up into their respective Representative Concentration Pathways (RCP) to form four groups; RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The CMIP-5 models that were used in this analysis are listed in Table 30-3. For each region, a linear regression was fitted to all 1x1 degree monthly SST data extracted from the models for each of three periods; 2010-2039, 2040-2069 and 2070-2099. The average change in SST was calculated by multiplying the slope of each linear regression by 360 (months) to derive the average change over each successive 30 year period. The table is divided into two sections, "Near-term (2010-2039)" – the average change in SST over the next 30 years, and "Long-term (2010-2099)" – the total change from 2010-2099, which was calculated by adding the average change of the three 30 year periods from 2010 to 2099. This is a simplified method to account for slight non-linearity in SST change over the 90 year period.]

30.3.1.2. Sea Level

The Ocean has expanded as a result of its increased heat content (3.7.2) and has expanded in mass (reliable records begin in 2002) mainly as a result of water being added from melting glaciers and ice sheets on land. As a result of the thermosteric and mass components, it is *virtually certain* that Global Mean Sea Level (GMSL) has increased between 1.4 and 2.0 mm yr^{-1} over the 20th Century and between 2.7 and 3.7 mm yr^{-1} since 1993 [(99% confidence; WGI 3.7.6]. It is also considered *very likely* that sea level rise has accelerated over the past two centuries and that rates are tenfold higher than the relatively high rates that occurred during the late Holocene [WGI Chapter 3, Chapter 5, 13.2.1–2, Figure 13.3].

Measurement of sea level rise using satellite altimetry, oceanographic buoys and floats (e.g. Argo Program) and tidal gauges reveal that sea level rise varies geographically, with rates three times higher than the global average sea level rise in the Pacific Warm Pool (PWL) located in the Western Pacific and South-East Asian region, and rates that are close to zero in many parts of the eastern Pacific. The high rates of sea level rise associated with the PWL are a result of the intensification of trade winds while the lower rates of sea level rise in the western United States are associated with changes in wind stress, both of which are strongly influenced by PDO variability (WGI 3.7.3, Figure 3.11 and FAQ 13.1). These differences are expected to vary on decadal timescales although it is very likely (*high confidence*) that 95% of the Ocean will experience significant regional changes in sea level over and above this source of variability (WGI Section 13.6.5, Figures 13.15–13.17).

Global Mean Sea Level is likely to increase by 0.7 m to 0.95 m by 2100 for Representative Concentration Pathways (RCP) of 2.6 and 8.5, respectively (*medium confidence*). Semi-empirical approaches project that sea level will increase well above 1 m by the end of the century (up to 1.5 m, WGI Table 13.6) although there is some discussion around assumptions associated with these approaches (WGI 13.4.1, 13.4.5). It is significant to note that sea level rise under these scenarios does not stop at 2100 and continues to occur for hundreds of years into the future, depending on the scenario in question. Central to this analysis is the millennial scale commitment to further sea level rise that is likely to arise from the melting of the Greenland and Antarctic ice sheets.

The combined effects of sea level rise and other factors such as increased storm intensity are very likely to increase the occurrence of extreme flooding events (WGI 13.7.2, 18 Figure 13.19). Regional flood risk depends on local topology, oceanography and other factors. While complete understanding of the associated risks is relatively undeveloped, significant coastal and low-lying areas, particularly in the Pacific Ocean and North Atlantic, face increased in flood risk (5.5). Future impacts from sea level rise include increasing penetration of storm surge into coastal areas, changing patterns of shoreline erosion (5.2.2.1) as well as the inundation of saltwater into coastal

aquifers (5.3.2.2.). While habitat may be lost, some examples of habitat expansion have been reported [*Brown et al.*, 2011]. Overall, changes to sea level and storm intensity are very likely to modify the habitats and hence coastal ecosystems such as beaches, salt marsh, coral reefs and mangroves (5.4.1.5), especially where rates of sea level rise are highest (e.g. South East Asia and the Western Pacific).

30.3.1.3. Surface Wind and Ocean Circulation

Atmospheric and ocean circulation (and their interaction) are centrally important to the chemical, physical and biological characteristics of the Ocean, determining crucial properties such as intensity of ocean ventilation, coastal upwelling, primary production, carbon export, and the spatial distribution and trophic interaction of plankton populations. While water is the major conveyor for transporting nutrients to land plants, the critical factor for transporting nutrients to the marine primary producers is ocean mixing driven by wind. Wind stress measurements from satellite and *in situ* observations have been collated within a number of international projects to produce reliable data sets on historic global wind patterns. In addition to an expanding set of ocean observing systems (e.g. Global Drifter and Argo Programs), there is a smaller archive of ocean circulation measurements, the small size of which ultimately limits our understanding of how ocean circulation has changed (WGI 3.6).

The National Center for Environmental Prediction (NCEP) Reanalysis Project, [*Kalnay et al.*, 1996] provides an opportunity to explore regional changes that have occurred over the past 60 years (1951-2010, Figure 30-6). While there are large uncertainties associated with historic wind speed data generally (WGI 2.7.2) and overall confidence in wind trends is low (SREX 3.3), there are some specific trends that persist across multiple data sets and analyses. Wind stress (westerly winds) has increased since 1951 over the Southern Ocean (Figure 30-6A) which matches observations from satellites and island station data since the early 1980s (*medium confidence*, WGI 3.4.4). A progressive migration of the westerlies towards higher latitudes has also occurred over the past several decades [*Cai*, 2006.; *Cai and Cowan*, 2007]. These changes are affecting mixed-layer dynamics, nutrient flux, and ocean circulation. The transport of Indian Ocean waters into the South Atlantic has increased in response to latitudinal shifts in the Southern Hemisphere westerlies [*Bard and Rickaby*, 2009; *Biastoch et al.*, 2008a; *Biastoch et al.*, 2008b], with potential implications for the evolution of the MOC [*Friocourt et al.*, 2005] and consequently future climate.

Surface waves are influenced by wind stress although understanding trends remains a challenge due to the paucity of data sets. It is likely, however, that Significant Wave Height (SWH) has been increasing since the 1950s over the Southern Ocean (up to 5% per decade, WG1 3.4.6) and mid-latitudes of the North Pacific and Atlantic Oceans (winter season trends of 8-20 cm per decade; WGI 3.4.6, 2.7.2). Understanding how SWH will change over the coming decades and century remain *uncertain* over most of the ocean remains an important knowledge gap (WG1 3.4).

Parts of the tropical Pacific show a decrease in wind stress over the same period (Figure 30-6A) which is consistent with other studies [*Vecchi et al.*, 2006] and analyzes (WGI Figure 2.37). Reduced trade wind speed is consistent with Walker Circulation and appears to have a considerable anthropogenic forcing component [*Vecchi et al.*, 2006]. Winds speeds have increased within some Eastern Boundary Upwelling Systems (e.g. California Current, Figure 30-6A; WG1 2.7.2). Changing wind regimes have the potential to influence Mixed-Layer-Depth (MLD) and upwelling intensity in highly productive sub-regions of the world's oceans although agreement is low as to whether or not upwelling will intensify across all areas [*Bakun*, 1990; *Bakun et al.*, 2010]. While there are many uncertainties with how wind stress will change under future changes to global climate, evidence from the tropical Pacific is consistent with predictions of further weakening of tropical atmospheric circulation under the influence of anthropogenic forcing [*Vecchi et al.*, 2006]. These changes are closely linked to patterns (and are likely to influence) of long-term variability associated with ENSO, NAO and SAM although observations are too limited in space and time to be able to separate anthropogenic trends from natural variability (WGI 3.5).

There is growing evidence that major circulation systems have changed. It is very likely, for example, that the subtropical Gyres (STG)s within the three ocean basins have expanded and strengthened since 1993 (WGI 3.5), and it is *as likely as not* that these changes are associated with an anthropogenic driver [*Signorini and McClain*, 2012].

There is *limited evidence* for other large-scale trends in major features of ocean circulation (e.g. Atlantic Meridional Overturning Circulation, AMOC, Indonesian flow-through) at this point (WGI 3.6). Global climate models need firstly to capture the large-scale changes in wind in order to accurately predict changes in primary production. Primary production, however, is also strongly dependent on regional and local processes down to frontal and eddy-forming scales implying that high resolution predictions of wind stress are also needed and represent an essential knowledge gap.

30.3.1.4. Solar Radiation and Clouds

Solar radiation plays a crucially important role in the biology of marine organisms. Not only as a source of energy for photosynthesis but it is also as a potential co-stressor in temperature related stress such as seen during mass coral bleaching and mortality events [*Hoegh-Guldberg*, 1999]. Global surface solar radiation (from the NCEP/NCAR Reanalysis Project, *Kalnay et al.* [1996]) decreased 4.3 $W.m^{-2}decade^{-1}$ from the 1950s until 1991 after which it increased at 3.3 $W.m^{-2}decade^{-1}$ until 1999 [*Ohmura*, 2009; *Wild*, 2009]. Changes in solar radiation and cloudiness from 1951 to 2010 vary regionally (Figure 30-6 B, C). The largest increases in solar radiation and decreases in cloudiness from 1951 to 2010 occurred in the tropical Pacific. These observations are consistent with the eastward shift in tropical convection and total cloud cover from the western to central equatorial Pacific over the 20th Century and with the long-term weakening of the Walker circulation (WG1 2.5.7.3). Decreases in cloud cover from 1951 to 2010 are also visible in the southern Indian, Pacific and Atlantic Oceans. Changes in cloud cover and solar radiation were correlated with broad changes in surface ocean salinity as a result of associated changes in heating of the ocean surface, cloud, and rainfall [*Deser et al.*, 2004]. Projections of how cloudiness, solar insolation and precipitation are likely to change as the planet warms have low levels of confidence due to the large interannual variability (ENSO, PDO), short observation time series and uneven spatial sampling, particularly early in the record (before 1950; WG1 2.5.8). Understanding these changes, however, represents a significant knowledge gap and area of future research.

[INSERT FIGURE 30-6 HERE
Figure 30-6: Absolute change over 50 years calculated using regression analysis of data from 1951-2010 (A) Wind Speed as the absolute change in $m.s^{-1}$; (B) Solar radiation as change at the surface of incoming solar insolation in Wm^{-2}; (C) Cloud Cover as the absolute change in total cloud fraction (i.e. If at the beginning of the period the cloud fraction was 0.6 and 0.5 at the end of the period, the change would be -0.1) using NCEP re-analyzed data (www.esrl.noaa.gov); and (D) Salinity as the percentage change from 1960-2010 [reproduced using the data of Durack and Wijffels, 2010]. Data for (A), (B) and (C) were derived from the NCEP/NCAR Reanalysis [*Kanamitsu et al.*, 2002]. Monthly mean values for wind speed, total cloud cover and downward solar radiation flux (solar insolation) were obtained from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html. At each 1x1 degree grid cell, a linear regression was calculated for each of wind, cloud and solar insolation. The slopes were then multiplied by 600 (months) to calculate the average change over a 50 year period.]

30.3.1.5. Storm Systems

Storm systems range from small atmospheric disturbances to large and violent cyclones, typhoons and hurricanes, and can have both positive and negative influences on ocean ecosystems. As agents of water column mixing, storms can remix nutrients from deeper areas into the photic zone of the ocean, stimulating productivity. Storms can also reduce local sea temperatures and associated stress by remixing heat into the deeper layers of the ocean [*Carrigan and Puotinen*, 2011]. Storms are often highly destructive, however, and can destroy coastal infrastructure and habitats such as coral reefs and mangrove forests which can take decades to recover [*De'ath et al.*, 2012].

There is *robust evidence* that the frequency of the most intense cyclones in the Atlantic has increased since 1987 (WG1 2.6.3) and *robust evidence* of inter-decadal changes in the storm track activity within the North Pacific and North Atlantic [*Lee et al.*, 2012]. There is also statistically significant evidence of a decrease in tropical cyclones that impacted the East Australian coast is the 19th century, with a significant interaction with long-term variability and land-falling cyclones being twice as common in La Niña versus El Niño years (*high confidence,* [*Callaghan and Power*, 2011]. There has been an increase in the number of intense wintertime extra-tropical cyclone systems since

the 1950s in the North Pacific. Similar trends have been reported for the Asian region although analyses are restricted by limitations in terms of the spatial and temporal coverage of reliable records (WG1 2.6.4).

Higher sea temperatures and specific humidities is *likely* to result in fewer yet more intense and damaging storm systems [*Bengtsson et al*., 2009; *Grinsted et al*., 2010]. Wind velocity of tropical cyclones is likely to increase under the influence of warming oceans although the frequency will either decrease or remain unchanged (WGI, 3.4.4). The number of extra-tropical and tropical storm events are *likely* to decrease while average storm intensity is likely to increase [*Bengtsson et al*., 2006; *Bengtsson et al*., 2009; *Landsea et al*., 2010], especially in the Western Atlantic, north of 20°N [*Bender et al*., 2010]. There is *medium confidence* that extra-tropical storm tracks will shift polewards (WGI, 3.4.5). Coastal ecosystems and human communities are likely to experience greater storm surge impacts as increased storm intensity interacts with rising sea levels [SREX 3.5.3, 3.5.5].

30.3.1.6. Thermal Stratification

Greater heat content has resulted in a 4% increase in thermal stratification of the upper layers of the Ocean (0-200 m, 40 year record) except in the case of the Southern Ocean (WG1 3.2.2). Increasing thermal stratification has reduced ocean ventilation and the depth of mixing in most ocean sub-regions (*medium confidence*, 6.3.2, 6.5.2). This in turn reduces the availability of inorganic nutrients and consequently limits primary productivity (*medium confidence*, 6.1.1, 6.2.2.1, 6.2.2.2.3). This has been observed in the STGs which dominate the three major ocean basins (30.5.6), and less so in high-latitude regions where winter convection and deep-water formation are dominant seasonally.

The continued warming of the surface layers of the ocean will *very likely* further enhance stratification and increasingly limit the nutrient supply to euphotic zone. There is *medium evidence* to suggest that the associated loss of primary productivity may be compensated for by enhanced upwelling at high latitudes and from the increasing input of nutrients from coastal systems from human activities (6.1.1.5). The response of upwelling to global warming is *likely* to vary between regions and represents a complex interplay between local and global variables and processes (Box 30-1).

_____ START BOX 30-1 HERE _____

Box 30-1. Upwelling Intensification, Stratification-Ventilation, and Primary Productivity

Bakun [1990] hypothesized that if atmospheric pressure gradients between land and sea expand due to global warming, meridional wind stress that causes upwelling could intensify (Figure 30-16). Empirical support for this hypothesis is equivocal *Bakun* [1990] found supporting trends in some EBUEs, but not others. Similarly, *Narayan et al*. [2010] found mixed results depending on the data sets used. *Garcia-Reyes and Largier* [2010] observed increasing winds and cooling for coastal locations off north-central California (from 36°N to 39°N), but no change to the north or south, while [*Perez et al*., 2010] found that upwelling clearly weakened in the northern Canary Current. Thus trends may vary spatially within systems. Upwelling-favorable winds could lead to increased nutrient input and primary productivity, increasing winds could also result in increased turbulence and offshore advection, factors that may reduce productivity on continental shelves [*Botsford et al*., 2003; *Cury and Roy*, 1989]. In this way, increased upwelling may be associated with increased nutrient input to the euphotic zone, but decreased primary and secondary production.

[INSERT BOX FIGURE HERE
Caption: Diagram illustrating the interaction between land and coastal sea temperature, wind direction and strength, and coastal upwelling.]

More recently, *Rykaczewski and Dunne* [2010] proposed the “stratification-ventilation” hypothesis which hypothesises that climate change could result in enhanced nutrient input and productivity at regional scales. Focusing on the California Current, GCMs were used to show that future increased stratification in the western and central North Pacific could alter the characteristics of waters upwelled in the California Current, with increasing

nitrate concentrations being a primary result. The basic argument in this case is that reduced ventilation and mixing of deep, nutrient-rich waters into the euphotic zone over much of the ocean allows continued accumulation of remineralized nutrients in subsurface waters. In sub-regions where these nutrient-enriched waters are forced into the euphotic zone by upwelling processes, nutrient supply and primary production may increase. Thus, primary productivity in the EBUEs may benefit from reduced utilization of nutrients in adjacent, well stratified sub-regions.

_____ END BOX 30-1 HERE _____

30.3.2. Chemical Changes

30.3.2.1. Surface salinity

Ocean salinity varies regionally and is an outcome of the balance between evaporation and the precipitation water from the atmosphere [*Durack and Wijffels*, 2010]; WG1 3.3). Evaporation-dominated regions such as the STGs, Atlantic (except in the Gulf of Mexico and South America; WG1 3.3.3.2) and Western Indian Oceans (Arabian Sea, WG1 3.3.3.1) have elevated salinity, while areas of high precipitation such as the North Pacific, north-eastern Indian Ocean and the eastern Pacific have relatively low salinities (WG1 3.3.3.1 Figure 30-5D). There is *very high confidence* (>99%) that most of these areas have continued to change in the same direction (i.e. a trend of increasing salinity in areas of high salinity and one of decreasing salinity in areas of low salinity (*Durack and Wijffels* [2010], Figure 30-6D).

Salinity trends are strongly consistent with the amplification of the global hydrological cycle [*Durack et al.*, 2012; *Pierce et al.*, 2012], a consequence of a warmer atmosphere producing greater precipitation, evaporation and extreme events (WG1 3.3.4, Figure 10.14a). These trends are consistent with increases in global temperature, and lead to the conclusion that "it is therefore *likely* that some of the observed changes in surface salinity in the 20th and the early 21st century are attributable to anthropogenic forcing" (WG1 10.4.3, Figure 10.14). Changes in salinity and temperature are consistent with changes expected due to anthropogenic forcing of the climate system and are inconsistent with the effects of natural climate variability, either internal to the climate system (e.g. ENSO, PDO) or external (e.g. solar forcing or volcanic eruptions, [*Pierce et al.*, 2012]. There are *high agreement* between CMIP3 climate models that these trends in ocean salinity are expected to continue as average global temperature [*Terray et al.*, 2012]. Ramifications of these changes are largely uncertain but are of great interest given the role of ocean salinity and temperature in fundamental processes such as the AMOC.

30.3.2.2. Ocean Acidification

Increased atmospheric CO_2 from human activities has increased the flux of CO_2 into the Ocean, resulting in decreased ocean pH as well as carbonate and bicarbonate ion concentrations (Box CC-OA). The extent to which the added influx of CO_2 into the Ocean has acidified and influenced the tendency for aragonite or calcite (polymorphs of calcium carbonate) to precipitate into the shells and skeletons of marine organisms depends mostly on the solubility of CO_2 and calcium carbonate, both of which decrease as temperature increases or depth decreases. Other factors such as atmosphere-ocean heat exchange, ocean circulation, and land-sea interactions (WG1 6.4) play significant roles in determining the saturation state of seawater for the polymorphs of calcium carbonate. Consequently, pH and the saturation states of aragonite and calcite are naturally lower at high latitudes and in upwelling areas (e.g. Eastern Pacific upwelling, Californian Current) which may be relatively more vulnerable to ocean acidification as a result [*Gruber et al.*, 2012](Figure 30-7 A, B). These two variables also decline with depth, calcite reaching its saturation horizon between 3,000 and 4,500 m, and aragonite reaching its saturation horizon between 1000 m and 2500 m in the Pacific and Atlantic oceans respectively [*Orr et al.*, 2005].

Surface ocean pH has declined by approximately 0.1 pH units since the beginning of the Industrial Revolution (*very high confidence*, WG1, 3.8.2, Box 3.2) with significant shoaling of the saturation horizons of both polymorphs of calcium carbonate [*Orr et al.*, 2005]. Oceanographic studies have measured the ongoing decline in ocean pH (–0.0015 and –0.0024 pH units per year; WGI 3.8.2, Figure 3.17) and the saturation state of calcium carbonate

polymorphs (WG1 Figure 3.17). These changes can be strongly attributed to the increase in anthropogenic CO_2 emissions to the atmosphere (*very high confidence*, WGI 3.8.2, Box 3.2 and Table 10.1) and are at least 10 times faster than accumulation of atmospheric CO_2 than during the Paleocene-Eocene Thermal Maximum (PETM; 6.1.2, *high confidence*). The impacts of ocean acidification on marine organisms and ecosystems has emerged as a major concern especially given the *robust evidence* that the current chemistry of the ocean is outside where it has been for million years [*Pelejero et al.*, 2010; *Zeebe*, 2012]. At current rates of atmospheric CO_2 increase, changes to the chemistry of the ocean will surpass any seen over the last 40 million years [*Hoegh-Guldberg et al.*, 2007; *Raven et al.*, 2005; *Tyrrell and Zeebe*, 2004] and possibly 300 million years (6.1.2).

Observations from a wide range of laboratory, mesocosm, and field studies reveal that marine organisms and ocean processes are sensitive to levels of ocean acidification projected under elevated atmospheric CO_2 (Box CC-OA, 6.2.2, 6.3.4, [*Kroeker et al.*, 2013], *high confidence*). Ecosystems that are characterised by high rates of calcium carbonate deposition (e.g. coral reefs, plankton communities) are sensitive to decreases in the saturation states of aragonite and calcite (*high confidence*). These changes are *very likely* to have broad consequences such as the loss of three-dimensional coral reef frameworks [*Dove et al.*, 2013; *Hoegh-Guldberg et al.*, 2007] and restructuring of food webs at relatively low concentrations of atmospheric CO_2. Similarly, organisms sensitive to changes in pH with respect to physiological processes such as respiration and neural function are also expected to respond to the rapid changes in pH and ocean chemistry (6.3.4). Due to the relative short history of ocean acidification studies, and the current expanding effort to understand this problem, there are a growing number of organisms and the processes that are being identified as sensitive to the influence of anthropogenic changes to ocean chemistry.

Projected changes to the atmospheric CO_2 will further acidify the ocean and change its chemistry (Figure 30-7; WG1 Figure 6.28). Doubling CO_2 will decrease ocean pH by another 0.1 pH units and decrease carbonate ion concentrations by approximately 100 mmol kg^{-1} (from an average of 250 mmol kg^{-1}; *high confidence, Orr et al. [2005]*)(WG1 6.4, Figure 6.28). The saturation horizons will also become significantly shallower in all oceans, with the aragonite saturation horizon line between 0 and 1500 m in the Atlantic and, 0 and 600 m (poles versus equator) in the Pacific Ocean [*Orr et al.*, 2005] WG1 6.4, Figure 6.28). Trends towards under-saturation of aragonite and calcite will also depend on ocean temperature, with polar waters expected to be undersaturated with respect to aragonite and calcite within a couple of decades (Box CC-OA; 6.4.4). These changes will also be accompanied by a shoaling of the aragonite and calcite saturation horizons that is *very likely* to have serious ramifications for deep water communities such as deep water scleractinian corals and other benthic organisms [*Guinotte et al.*, 2006].

[INSERT FIGURE 30-7 HERE
Figure 30-7: A. Surface pH and B. aragonite saturation state of the Ocean at different atmospheric CO_2 levels simulated by the University of Victoria Earth System Model. The fields of pH and aragonite saturation state are calculated from the model output of dissolved inorganic carbon concentration, alkalinity concentration, temperature, and salinity, together with the chemistry routine from the OCMIP-3 project (http://www.ipsl.jussieu.fr/OCMIP/phase3).]

30.3.2.3. Oxygen Concentration

Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms (6.2.2.1.). Oxygen concentrations vary across the ocean basins, tending to be lower in the eastern Pacific and Atlantic basins, and northern Indian Ocean (Figure 30-8; 6.1.1.3). By contrast, some of the highest concentrations of oxygen are associated with cooler high latitude waters (WG1 Figure 3.19). Long-term records of oxygen concentrations in ocean waters are rare. However, there is high agreement that open ocean oxygen concentrations in the thermocline have declined by 0.09 to 0.34 μmol kg^{-1} $year^{-1}$ since 1960 and it is *very likely* that the tropical oxygen minimum zones have expanded over recent decades (WG1 3.8.3; *Stramma et al.* [2008]). These changes are consistent with the solubility of oxygen declining with higher temperatures and with increased water column stratification reducing ocean-atmosphere ventilation. Analysis of ocean O_2 trends over time [*Helm et al.*, 2011a] reveals that the basic phenomenon of O_2 solubility decreasing with increased temperature is responsible for no more than 15% of the observed change. The remaining 85%, consequently, must be attributed to increased deep-sea microbial respiration and reduced O_2 supply from increased ocean stratification (WG1 Box 6.5 Figure 1). Eutrophication of coastal areas,

for example, can lead to increased transport of organic carbon into ocean habitats where microbial metabolism is stimulated resulting in a rapid drawdown of oxygen [*Bakun et al*., 2010; *Rabalais et al*., 2009; *Weeks et al*., 2002].

It is *likely* (*limited evidence, medium agreement*) that areas of low O_2 concentrations in deep water are expanding in many parts of the world (WGI 3.8.3) with impacts on marine life including mass mortality and the subsequent exclusion of fish and other metazoans from expanding "dead zones" (*high confidence*, [*Diaz and Rosenberg*, 2008](6.2.2, 6.3.3). These areas are rapidly expanding due to regional human drivers not directly related to climate change (i.e. eutrophication of coastal areas) in addition to drivers that are (e.g. increasing sea temperature, increasing stratification, changes in terrestrial run-off and reduced ventilation from changing wind stress). Climate change at a decadal time scales is also driving the widespread increase in hypoxia through the reduction in oxygen concentrations arising due to reduced solubility, temperature effects on microbial respiration, and increased water column stratification. The subarctic Pacific is perhaps the best example of an ocean basin where physical forcings are clear, where Siberian warming leads to reduced ice formation, a reduction in dense water formation and a weakening oxygen transport into the interior ocean [*Nakanowatari et al*., 2007].

The development of hypoxic conditions (generally defined as O_2 concentrations below 60 μmoles kg^{-1}) over recent decades has been documented across a wide array of ocean sub-regions including SES (Black and Baltic Seas), the Arabian Gulf, and the California, Humboldt and Benguela current systems (Figure 30-8), where eruptions of hypoxic, sulfide-laden water have occurred [*Weeks et al*., 2002]. Localized seasonal hypoxic zones have emerged in economically valuable coastal areas such as the Gulf of Mexico [*Rabalais et al*., 2010; *Turner et al*., 2008], the Baltic Sea [*Conley et al*., 2009] and Black Sea [*Kideys*, 2002; *Ukrainskii and Popov*, 2009], in connection with nutrient fluxes from land. Over a vast region of the Eastern Pacific stretching from southern Chile to the Aleutian Islands, the minimum pO_2 threshold (< 2 $mg.l^{-1}$ or 60 mmol kg^{-1}) is found at only 300-m depth and upwelling of increasingly hypoxic waters is well documented [*Grantham et al*., 2004]. Hypoxic waters in the northern Arabian Sea and Bay of Bengal are located close to continental shelf depths. Long-term measurements are revealing that oxygen concentrations are declining in these waters, with *medium evidence* that economically significant mesopelagic fish populations are being threatened [*Koslow et al*., 2011]. The Atlantic Ocean differs from the Pacific and Indian Ocean as hypoxic conditions in this respect are largely limited to the regions at and adjacent to the two EBUE due to its better ventilation. The calculation of hypoxia profiles according to an assumed critical threshold of 60 mmol kg^{-1} are illustrative although this can convey an overly simplistic message given that critical concentrations of O_2 are species and life history stage specific, showing a great dependence on body size and/or temperature. This variability in sensitivity is critical to how ecosystems are likely to respond to this aspect of climate change (6.3.3).

It is *very likely* that further increases in ocean temperature will lead to decreased oxygen concentrations due to the effect of temperature on O_2 solubility and water column stability (reduced ocean ventilation). There is *high agreement* among modelling studies that the total oxygen within the ocean will decline under future scenarios (WG1 Table 6.14). The outcomes of these global changes will be influenced by regional differences in wind stress, coastal processes, and the production and consumption of organic matter by microbes.

[INSERT FIGURE 30-8 HERE
Figure 30-8: Map of the depth [*Hofmann et al*., 2011] at which a critical value of partial pressure of O_2 of 60 matm occurs which is widely accepted as threatening to marine life on continental shelves (200m depth). Conventional maps of oceanic oxygen values report simple mass properties with no temperature or depth dependence; a better rendition of the availability of O_2 to marine life is provided by the partial pressure, which includes the temperature terms. Critical sub-regions in the eastern and northern Pacific and in the northern Indian ocean stand out. In these areas quite modest upward expansion of the depth at which the critical pO_2 level occurs can have negative effects on major fish populations. Note: not all areas have been included – for example, significant hypoxia in the Gulf of Mexico is not been shown.]

30.4. Global Responses by Marine Organisms to Climate Change (including Ocean Acidification)

There has been a rapid increase in studies that focus on climate change impacts on marine ecosystems since AR4 ([*Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al*., 2013] representing an opportunity to examine and

potentially attribute detected changes within the Ocean to climate change. *Poloczanska et al*. [2013] applied the 'vote-counting' approach used by *Parmesan and Yohe* [2003]; *Root et al*. [2003] and *Rosenzweig et al*. [2008] to show a coherent pattern in responses of ocean life to recent climate change across regions and taxonomic groups using a global database of observed responses (1735 responses in 857 species or assemblages from 208 peer-reviewed papers). (Figure 30-9; [*Poloczanska et al*., 2013]. Observations were defined as those where the authors of a particular paper assessed the consistency of change in a biological parameter (namely distribution, phenology, abundance, calcification, demography or community composition) with climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) data after 1990 were included; and (3) observations spanned at least 19 years, to minimize bias resulting from short-term biological responses to natural climate variability. Approximately 90% of the studies identified temperature as the primary driver of change, with the remainder focusing on sea ice, pH and climate oscillation, where changes have been explicitly linked to global warming.

[INSERT FIGURE 30-9 HERE
Figure 30-9: (A) 1735 observed responses to climate change from 208 single- and multi-species studies showing responses that are consistent with climate change (blue), opposite to expected (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite plus equivocal) observations within each region. (B) Frequency of observations by latitude. (C) South-west Pacific. (D) North-east Atlantic. (E) California Current. (F) North-west Pacific (Poloczanska et al 2013).]

The results of this meta-analysis suggest that climate change is having an impact on species in many different ways across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, 84% were in a direction that was consistent with climate change (Fig. 30-10). For these, consistency was variable according to taxonomic group (Figure 30-10A), latitudinal band (Figure 30-10B), and biological response parameter (Figure 30-10C). Despite remaining knowledge gaps, especially in equatorial sub-regions and the Southern Hemisphere, it is clear that recent climate change has already had widespread impacts on marine organisms and ecosystems.

[INSERT FIGURE 30-10 HERE
Figure 30-10: Percent of responses consistent with climate change predictions. Mean and standard error of responses by (A) taxa, (B) latitudinal region and (C) response measure show significantly higher consistency than expected from random (dashed line at 50% consistency). Solid line is the mean across all observations. Significance of results is listed next to labels (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Sample sizes are listed to the right of each row.]

The overall mean (± SE) rate of re-distribution for marine biota was 72.0 ± 13.5 km decade^{-1} measured at leading range edges and 15.8 ± 8.7 km decade^{-1} at trailing edges, with most of the data collected from 1950 onwards (Figure 30-10B) revealing much higher rates of migration than reported for terrestrial species. The average rate of change on land was 6.1 ± 2.4 km decade^{-1} when calculated across taxa [*Parmesan and Yohe*, 2003] or 19.7 ± 3.7 km decade^{-1} calculated across regional taxonomic groupings [*Chen et al*., 2011]. Similarly, spring timing showed advances of -4.4 ± 0.7 day.decade^{-1} in marine systems (Figure 30-11A [*Poloczanska et al*., 2013]), contrasting with -2.8 ± 0.35 day.decade^{-1} for terrestrial species [*Parmesan*, 2007]. Similar trends are seen for the delayed arrival of fall/winter in both hemispheres.

[INSERT FIGURE 30-11 HERE
Figure 30-11: Rates of change in (A) phenology (days.decade^{-1}) measured during spring (red) and summer (brown); and (B) distribution (km.decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), and trailing edges (brown). O (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward) and negative phenological changes are consistent with warming (generally earlier). Means ± standard error are shown, with number of observations and significance (*p<0.1, **p<0.05, ***p<0.01); Poloczanska et al, 2013).]

The faster expansion rates of leading edges compared to contraction of trailing edges can be partly explained by the speed and direction at which isotherms propagate across the Ocean's surface [*Burrows et al*., 2011; *Loarie et al*., 2009] in study regions. Both the leading and trailing range edges for ectothermic marine organisms are likely to be equally responsive to warming temperatures [*Sunday et al*., 2012]. The velocity of isotherm migration in the ocean over 1960-2009 [*Burrows et al*., 2011] varies considerably, with locally fast and slow sub-regions. Rapid velocities (>50 km.decade^{-1}) were observed in the North Sea, the sub-Arctic Pacific and Atlantic, and within 15° of the equator, implying a risk of large ecological responses (Figure 30-3B, [*Burrows et al*., 2011]). Rates of climate change, such as climate velocity, over longer time periods can help to explain both present-day distribution patterns and shifts in biodiversity [*Sandel et al*., 2011].

Poloczanska et al. [2013] reveal that climate change is resulting in changes to organisms and ecosystems within the world's oceans (*robust evidence, high agreement,* and *high confidence*). Diagnostic fingerprints, uniquely predicted by twentieth century climate trends, provide convincing evidence that climate is the primary driving force behind the observed biological changes, strengthening the attribution of detected changes to climate change (Parmesan and Yohe 2003). These include concurrent increases of 'warm-water' species and decreases of 'cool-water' species, as expected with climate change, within regions. Consistent responses were recorded across multiple poleward or equatorward edges of distributions that were widely separated (such as for fish populations in north-west Atlantic and north-east Atlantic, and discussed in regional assessments below).

30.5. Regional Impacts, Risks, and Vulnerabilities: Present and Future

This section explores the impacts, risks and vulnerabilities of climate change for the seven sub-regions within the Ocean. There is considerable variability from region to region, especially in the extent and interaction of climate change and non-climate change stressors. While the latter may complicate attribution attempts in many sub-regions, interactions between the two types of stresses may also represent opportunities to reduce the overall impact on marine organisms and processes by environmental changes being driven by climate change (including ocean acidification).

30.5.1. High-Latitude Spring Bloom Systems

High-latitude Spring Bloom Systems (HLSBS) stretch from 35º N and S to the edge of the winter sea ice and provide 36% of world's fishery catch (Table 30-1, Figure 30-1). Strong seasonal cycles of primary productivity are pronounced at high latitudes, which create phytoplankton spring-bloom dynamics, and follow the latitudinal gradient in light intensity [*Racault et al*., 2012]. Efficient transfer of marine primary and secondary production to higher trophic levels, including commercial fish species, is influenced by the magnitude and spatial and temporal synchrony between successive trophic production peaks [*Beaugrand and Reid*, 2003; *Beaugrand et al*., 2003; *Cushing*, 1990; *Hjort*, 1914].

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The North Atlantic is one of the most intensively fished ocean sub-regions. The major areas for harvesting marine living resources span the eastern American, European and Icelandic shelves [*Livingston and Tjelmeland*, 2000]. In addition, the Deep Sea regions of the Nordic Seas and the Irminger Sea contain large resources of pelagic and mesopelagic fish such as herring, blue whiting, mackerel and redfish. The region covers a wide latitudinal range from 35º to 80ºN, and, hence, a large span in thermal habitats. This is reflected in the latitudinal gradients from subtropical/temperate species along the southern fringe to boreal/arctic species along the northern fringe.

The North Atlantic HLSBS shows prominent and robust warming trend resulting in an increase in temperature of 3.97ºC from 1955 to 2005 (Table 30-2). Since the 1970s, the Atlantic Ocean has warmed more than any other Ocean

basin (0.3ºC decade^{-1}; Table 30-2; WGI Chapter 3) with greatest warming rates over European continental shelf areas such as the southern North Sea, the Gulf Stream front, the sub-polar gyres and the Labrador Sea [*González-Taboada and Anadón*, 2012; *Lee et al*., 2011; *Levitus et al*., 2009; *Mackenzie and Schiedek*, 2007a; b]. Nearly half of the basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming, with the rest being contributed by the Atlantic Multi-decadal Oscillation [*Wang and Dong*, 2010].

Observations and modeling indicate increased primary production with increasing temperature [*Mueter et al*., 2009; *Steinacher et al*., 2010], and poleward displacement of species [*Cheung et al*., 2011; *Stenevik and Sundby*, 2007]. The subsequent examples, mainly from the Barents, Nordic, and North Seas how warming from the early 1980s has influenced North Atlantic ecosystems where substantial biological impacts have been observed including large-scale modification of the phenology, abundance and distribution of plankton assemblages and reorganization of fish assemblages [*Beaugrand et al*., 2002; *Edwards*, 2004; *Edwards and Richardson*, 2004; *Nye et al*., 2009; *Simpson et al*., 2011; *Tasker*, 2008] Changes are also evident towards the southern fringe of North Atlantic HLSBS where southern species of molluscs and fish have expanded into the Bay of Biscay [*Bañón et al*., 2010; *Guerra et al*., 2002] and juvenile Bluefin Tuna (*Thunnus thynnus*) and Albacore Tuna (*Thunnus alalunga*) on summer feeding migrations are arriving earlier from 1967-2005 due to warming and subsequent shifts in prey assemblages [*Dufour et al*., 2010].

The past decade has been the warmest decade ever recorded in the Barents Sea resulting in large populations of krill, shrimp, pelagic and demersal fish stocks linked to the Atlantic and boreal ecosystem of the Barents Sea [*Johannesen et al*., 2012]. The relatively warm Atlantic waters have advanced northward and eastward [*Årthun et al*., 2012] and sea-ice has retreated along with the Arctic water masses. As a result, boreal euphausiids, which are mainly confined to the Atlantic water, have increased in biomass and distribution [*Dalpadado et al*., 2012] enhancing growth of young cod *Gadus morhua* (boreal) as well as the more Arctic (arcto-boreal) capelin (*Mallotus villosus*). The amphipods of more Arctic origin have decreased, resulting in poorer feeding conditions for polar zooplankton predators such as polar cod (*Boreogadus saida*). Blue whiting (*Micromesistius poutassou*) which spawn west of the British Isles, feed on zooplankton in the Norwegian Sea during the summer. During the recent warming period, the summer feeding distribution of the whiting extended into the Barents Sea. In summary, the long-term trend of pelagic fish species has increased in the Barents Sea, although with pronounced decadal-scale oscillations superimposed over long-term climate trends. The recruitment to boreal fish stocks like cod, haddock, and herring has increased in the Barents Sea [*Eriksen et al*., 2012]. Climate change by 2100 is *virtually certainly going* to impact the northern fringes of the Atlantic HLSBS with increases in zooplankton production of 20 % in the Barents Sea [*Ellingsen et al*., 2008] as temperatures increase and Atlantic species replace the Arctic ones (*medium evidence, high agreement,* and *high confidence*). Together with poleward shifts of fish species, a substantial increase in fish biomass and catch is also *very likely* [*Cheung et al*., 2011]. However, the continuous temperature increase is *very likely* to cause discontinuous changes in life cycle conditions for some species like the capelin which feeds in summer at the ice edge and spawns in spring at the southern Atlantic Norwegian/Murman coast of the Barents Sea. The limited migration potential for this small pelagic fish is *likely* to cause it to switch spawning areas to the similar, but far separated spawning grounds at the Novaja Semlja coast with the only alternative to go extinct [*Huse and Ellingsen*, 2008].

The Norwegian Sea is one of the two core regions for the herbivore copepod *Calanus finmarchicus* that is an important prey species for pelagic fish and early life-stages of all fish around the rim including the North Sea and the Barents Sea [*Sundby*, 2000]. *C. finmarchicus* is the main food item for some of the world's largest fish stocks such as the Norwegian spring-spawning herring (*Clupea harengus*), blue whiting (*M. poutassou*) and Northeast Atlantic mackerel (*Scomber scombrus*). These stocks have increased considerably during the recent warming from the early 1980s [*Huse et al*., 2012]. Also, the individual size of herring has increased enabling longer feeding migration routes to utilize zooplankton closer to more distant Arctic water masses towards northwest. Mackerel has advanced northward and westward into Icelandic waters [*Astthorsson et al*., 2012]. Since 2008, however, biomass of the pelagic fishes has decreased along with a decreasing biomass of the *C. finmarchicus*, indicating a switch in the system to a top-down control. This demonstrates that even though fish stocks are expected to increase in high latitude regions under climate change this increase is limited by the productivity in zooplankton.

There is *high confidence* that observed changes in the phenology of plankton groups in the North Sea is being driven by regional warming [*Edwards and Richardson*, 2004; *Lindley and Kirby*, 2010; *Lindley et al.*, 2010; *Schluter et al.*, 2010; *Wiltshire and Manly*, 2004; *Wiltshire et al.*, 2008]. Phenological responses of zooplankton were species-specific with substantial variation within functional groups. For example, the peak maximum abundance of the copepod *Calanus finmarchicus* advanced by 10 days from the 1960s to the 2000s, but it's warm-water equivalent, *C. helgolandicus,* did not advance [*Bonnet et al.*, 2005]. The appearance of larvae of benthic fauna in the meroplankton corresponds to the timing of adult reproductive cycles, so shifts in adult phenology [*Beukema and Dekker*, 2005; *Philippart et al.*, 2003] have implications for biological linkages between benthic and pelagic ecosystems [*Kirby et al.*, 2007; *Lindley et al.*, 2010]. The ranges of some cold-water zooplankton assemblages in the North-east Atlantic have contracted towards the Arctic since 1958, and many warm-water zooplankton assemblages (specifically copepods) have replaced them (*high confidence*), moving up to 1000 km northward [*Beaugrand*, 2009; *Beaugrand et al.*, 2002].

Fish communities from both the North-west and North-east Atlantic show distributional shifts (*high confidence*) although the direction of these changes varies among species. Fish communities are also shifting to greater depths due to warming [*Dulvy et al.*, 2008; *Nye et al.*, 2009; *Perry et al.*, 2005; *Tasker*, 2008]. In the North Sea, bottom temperatures in winter have warmed by 1.6°C (1980- 2004, [*Dulvy et al.*, 2008]. The whole demersal fish community shifted deeper by 3.6 m decade^{-1} over the period 1980-2004, although mean latitude of the whole community did not show net displacement [*Dulvy et al.*, 2008]. Within the community, cool-water specialists generally shifted northwards while abundant warm-water species shifted southwards reflecting winter warming of the southern North Sea. The cold winter temperatures of the shallow regions of the southern North Sea have acted to exclude species with warm-water affinities. Trawl survey data from the rapidly-warming southern North Sea suggests waves of immigration by southern species, such as red mullet (*Mullus surmuletus*), anchovy (*Engraulis encrasicholus*) and sardines (*Sardina pilchardus*), linked to increasing population sizes and warming temperatures [*Beare et al.*, 2005]. In the high-latitude North Atlantic diversity of zooplankton and fish has increased, as more diverse warm-water assemblages extend northward in response to changing environmental conditions [*Beaugrand*, 2009; *Hiddink and ter Hofstede*, 2008; *Kane*, 2007; *Mountain and Kane*, 2010; *ter Hofstede et al.*, 2010]. Southern (warm-water) species of fish have increased in abundance on both sides of the North Atlantic (*medium confidence*) [*Beare et al.*, 2005; *Collie et al.*, 2008; *Hermant et al.*, 2010; *Lucey and Nye*, 2010; *Simpson et al.*, 2011].

Range expansions and contractions linked to changing climate have also been found in benthic crustaceans, bivalves, gastropods, and polychaetes [*Berke et al.*, 2010; *Beukema et al.*, 2009; *Mieszkowska et al.*, 2007]. For example, the southern range of the common intertidal barnacle *Semibalanus balanoides* in the North-east Atlantic has been contracting at a rate of 15-50 km decade^{-1} since 1872, and the retreat is attributed to reproductive failure as winter temperatures warm [*Southward et al.*, 2005; *Wethey and Woodin*, 2008]. The warm-water competitor *Chthamalus montagui* of *S. balanoides* has increased in abundance to replace the niche vacated by *S. balanoides* [*Poloczanska et al.*, 2008; *Southward et al.*, 1995]. Changes in the distribution of seaweed species have been observed along the coastline of the Iberian Peninsula where a latitudinal gradient in temperature is observed all year despite summer upwelling. In particular, some large seaweeds with a cold-water affinity have contracted their distribution limits [*Díez et al.*, 2012; *Fernández*, 2011; *Lamela-Silvarrey et al.*, 2012] while species with a warm-water affiliation have expanded [*Lima et al.*, 2007].

Most of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing are from this region [*Edwards et al.*, 2010; *Poloczanska et al.*, 2013; *Southward et al.*, 2005; *Sundby and Nakken*, 2008; *Toresen and Østvedt*, 2000]. Meta-analysis of 288 long-term datasets of zooplankton, benthic invertebrates, fish and seabirds from the OSPAR Commission Maritime Area in the north east Atlantic showed wide-spread changes in distribution, abundance and seasonality that were consistent (75%) with expectations from enhanced greenhouse warming [*Tasker*, 2008]. The study bought together evidence of changes in ocean climate, and ecological responses across a range of species that encompassed both exploited and unexploited species from a variety of information types including peer-reviewed reports from ICES Working Groups [*Tasker*, 2008]. In particular, observations showed polewards shifts in zooplankton communities, increasing abundance of fish species in the northern part of their ranges and decreases in southern parts, and the expansion of benthic species into more northerly or less coastal areas.

The major part of the literature on climate impacts for the North Atlantic region covers time spans longer than for most other sub-regions of the Oceans. Even here, however, most of the literature is limited to the recent 30 to 50 years. The few publications covering the first half of the 20th century represent an important longer-term perspective to the impacts of climate change [*Astthorsson et al.*, 2012; *Bañón*, 2009; *Drinkwater*, 2006; *Sundby and Nakken*, 2008; *Toresen and Østvedt*, 2000]. For example, distinct changes in fauna were associated with a pronounced warming period of 1920-1940 [*Wood and Overland*, 2010] when fish and other fauna moved northward [*Drinkwater*, 2006; *Hátún et al.*, 2009; *Iversen*, 1934; *Southward et al.*, 1995]. The major lesson from these reports is that an almost similar large-scaled temperature increases occurred in the high-latitude North Atlantic from 1910s to the 1940s as that which occurred during the last 30 years, with similar basin-scale impacts on marine ecosystems. The former event was of great concern within the scientific community, particularly during the late 1940s and early 1950s [*Iversen*, 1934; *Tåning*, 1949; *Tåning*, 1953]. With the subsequent long-term cooling in the 1970s, however, discussion around climate impacts has unfortunately discontinued. The present centennial-long perspectives indicate that the major fraction of the impacts from the recent 30-year temperature increase is part of multidecadal changes with the crucial message that understanding the scenarios for the anthropogenic climate change over the next century is particularly important. We are only beginning to see the early contours of this development. Under the assumption that the long-term natural climate variability continues through 21st century with the same frequency and amplitude as during the 20th century we could expect that we have already reached a culmination of the multidecadal signal with only limited temperature increase over the next 20 years until again the anthropogenic and natural climate signal are adding up in the same direction. Under such a scenario, the climate of the North Atlantic climate is projected to change more rapidly around 2050 than ever recorded (*high confidence*).

30.5.1.1.2. North Pacific

Sub-decadal variability in the North Pacific HLSBS is dominated by ENSO [*Trenberth*, 1990], WGI Chapter 14). Like the North Atlantic HLSBS, the North Pacific HLSBS has shown high rates of warming, with an increase in average sea temperature of 4.62ºC from 1955 to 2005 (based on data from 1950 to 2009, Table 30-2). Decadal and longer periods of variability in the North Pacific are reflected in two principal modes; the Pacific Decadal Oscillation (PDO) with periodicities at both 15-25 y and 50-70 y in SST [*Mantua and Hare*, 2002; *Minobe*, 1997], and the Victoria Pattern [*Bond et al.*, 2003] and the North Pacific Gyre Oscillation (NPGO). The PDO exhibits SST anomalies of one sign along the eastern boundary and the opposite sign in western and central Pacific (WGI 14.6.6), The PDO has been reported to have an anthropogenic component thus confounding statistical approaches aimed at removing natural variability from ecological time-series [*Bonfils and Santer*, 2011]. The interplay of the phases of these modes of variability has strong influence on high-latitude Pacific ecosystems. In the space of three years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) [*McKinnell and Dagg*, 2010; *McKinnell et al.*, 2010]. This rapid change was accompanied by large changes in primary productivity, zooplankton communities and fish and seabirds [*Batten and Walne*, 2011; *Bi et al.*, 2011; *Keister et al.*, 2011; *McKinnell and Dagg*, 2010; *McKinnell et al.*, 2010].

Periods of broad-scale environmental regime shifts are observed across high-latitude ecosystems in the North Pacific (eastern Bering Sea and Gulf of Alaska) during 1976-78, 1987-89 and 1998-99. These periods were associated with regime shifts in forage fish that occurred in 1979-82, 1988-92 and 1998-2001. These changes indicate of how basin-scale variability such as PDO can manifest across distinct ecosystems [*Link et al.*, 2009a; *Link et al.*, 2009b; *Overland et al.*, 2008]. Climate regime shifts are characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter [*Alheit*, 2009; *Hunt et al.*, 2002; *Litzow and Ciannelli*, 2007; *Litzow et al.*, 2008]. Phenological shifts have been observed in the zooplankton communities of the North Pacific in response to decadal climate cycles with distinct changes noted after the climate regime shifts of the 1970s and 1990s [*Chiba et al.*, 2006; *Mackas et al.*, 1998]. In the North-west Pacific, springtime copepod abundance also increased linearly over the period 1960-2002 [*Chiba et al.*, 2006]. Regime shifts in the mid-1970s and late-1980s were also reported in the Kuroshio-Oyashio Extension (KOE) in the North-west Pacific with dramatic changes in pelagic ecosystems and sardine and anchovy stocks [*Chiba et al.*, 2008; *Yatsu et al.*, 2008]. Climate change model simulations show global warming could further alter the dynamics of the Kuroshio Current and the Kuroshio Extension dynamics over the coming century [*Sakamoto et al.*, 2005] that will alter timing, magnitude and structure

of spring-blooms in the western Pacific with implications for pelagic fish production and biogeochemical cycles [*Hashioka et al.*, 2009].

Commercial catches of salmon species in the North Pacific follow decadal climate changes [*Hare and Mantua*, 2000; *Mantua and Hare*, 2002]. Catches peaked in the warm periods of the 1930s-1940s and 1990s-2000s with 2009 yielding the highest to date, and warming trends may have contributed to recent peak in some sub-regions [*Irvine and Fukuwaka*, 2011; *Morita et al.*, 2006]. Anticipating ecological responses to future anthropogenic climate change also requires evaluation of the role changes to climate beyond warming *per se*. For example, declining sea level pressure (SLP) in the North Pacific is anthropogenically forced [*Gillett et al.*, 2003], and SLP in turn is related to atmospheric climate parameters (e.g., turbulent mixing via wind stress) that regulate commercially significant fish populations [*Wilderbuer et al.*, 2002].

The Bering Sea region is among the most productive of marine sub-regions, and includes the world's largest single-species fishery which fishes for walleye Pollock *Theragra chalcogramma* [*Hunt et al.*, 2010]. This region has undergone major changes in recent decades as a result of climate variability, climate change and fishing impacts [*Hunt et al.*, 2010; *Jin et al.*, 2009; *Litzow et al.*, 2008; *Mueter and Litzow*, 2008]. SSTs have increased at a rate of 0.23°C.decade^{-1} over 1982-2006 [*Mueter and Litzow*, 2008] but since 2006 it has been colder than the long-term average [*Coyle et al.*, 2011]. Seasonal sea ice cover strongly influences the Bering Sea ecosystem through regulating the spring bloom and extent of the "cold pool" ; an area of reduced water temperature <2°C on the northern Bering Sea shelf that is formed as a consequence of sea ice and is maintained over summer [*Hunt et al.*, 2010]. Seasonal sea ice has declined since the 1990s (to 2006), although there is no linear trend 1953-2006, and the initiation of spring ice retreat over the south-eastern Bering Sea shelf occurred earlier [*Wang et al.*, 2007a; *Wang et al.*, 2007b]. Concurrent with a retreat of the cold pool, bottom trawl surveys of fish and invertebrates show a significant community-wide northward distribution shift and a colonization of the former cold pool areas by subarctic fauna [*Mueter and Litzow*, 2008; *Wang et al.*, 2006a]. Total biomass (mean catch per unit effort) has increased dramatically in the northern survey area, including the area around the Pribilof Islands [*Mueter and Litzow*, 2008]. The shallow waters of the eastern Pacific Ocean are low in oxygen (Figure 30-8). Coastal upwelling along the continental shelf can cause mortality of coastal fishes and invertebrates [*Grantham et al.*, 2004], whereas decreasing oxygen concentrations at depth in the subtropics are explained by changes in the gyre circulation in response to 20th century climate change. The role of climate change in decreasing the oxygen concentration at higher latitudes remains unclear although changes in ocean mixing and ventilation are likely to be contributing factors [*Deutsch*, 2005].

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the southern hemisphere are much less pronounced and of smaller magnitude as those in northern hemisphere high-latitudes [*Yoder et al.*, 1993]. The southern hemisphere HLSBS is broadly bounded by the sub-tropical front (STF) and sub-Antarctic front. Associated with the STF is intense biological activity by bloom-forming coccolithophores (phytoplankton) [*Brown and Yoder*, 1994]. The calcifying plankton assemblages play a key role in carbon cycles in the region and the transport of carbon to deep ocean sediments. The coccolithophore *Emiliania huxleyi* has extended its range south of 60° in the south-west Pacific (141-145°E) over the two decades since 1983 [*Cubillos et al.*, 2007]. Although the drivers for this range extension are not clear, it is proposed that the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

While the South Pacific HLSBS has not shown warming overall (1950 to 2009, Table 30-2), some areas within the HLSBS have warmed very significantly. There is *high confidence*, for example, that the western Tasman Sea has shown enhanced warming since 1900 as compared to average global trends. This has been driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific STG and intensifying the southward-flowing East Australian Current (EAC) [*Cai*, 2006; *Hill et al.*, 2008; *Wu et al.*, 2012]. Model simulations suggest both stratospheric ozone depletion and greenhouse forcing contribute equally to the observed trend in wind stress [*Cai and Cowan*, 2007]. Coinciding with this warming and intensified EAC is the observation that a number of benthic invertebrates, fish and zooplankton are now found further south compared to mid-20th century [*Last et al.*,

2011; *Ling*, 2008; *Pitt et al.*, 2010]. We have *very high confidence* that warming has facilitated the establishment of the grazing urchin *Centrostephanus rodgersii* in eastern Tasmania during the late 1970s which has resulted in deleterious effects on macroalgal beds [*Banks et al.*, 2010; *Ling*, 2008; *Ling et al.*, 2008; *Ling et al.*, 2009].

30.5.1.2. Key Risks and Vulnerabilities

Projected changes to the temperature of surface waters matched those of the past 50 years, with average sea temperatures in the HLSBS increasing by 0.41-1.17°C in the near term (2010-2039) and by 1.91-4.84°C over the long term (2010-2099) under the 'Business-as-usual' (BAU) RCP8.5 scenario. Under the lower-case scenario considered here (RCP2.6), projected rates of warming are much lower: 0.13 - 0.79 °C in the near term (2010-2039) and -0.09 - 1.46 °C by 2100. Risks to HLSBS from even modest warming of surface waters include changes to basin- and regional-scale ocean circulation which is *very likely* to affect the transport of organisms and water masses, primary production with implications for food webs and carbon cycling, changes in distribution, phenology and productivity of species leading to reorganization of ecosystems, and the loss of subsurface habitat to hypoxia. An additional risk exists for sub-polar areas from the loss of seasonal sea-ice. Ocean acidification will produce additional and large-scale challenges. Both primary productivity and timing of the spring bloom in this region are very sensitive to environmental change. The magnitude of planktonic production is central to higher trophic level production. Climate induced changes in stratification strength and mixed layer depth can lead to decreased or increased phytoplankton production [*Behrenfeld et al.*, 2006]. The onset of spring warming within high latitude sub-regions is advancing by 2-2.5 days.decade^{-1} [*Burrows et al.*, 2011]. Latitudinal shifts in the distribution of phyto- and zooplankton communities will change the day-length regimes experienced with impacts on growth and survival [*Beaugrand*, 2009; *Ito et al.*, 2010; *Shoji et al.*, 2011]. Alteration of the structure and composition of plankton communities will propagate through food webs because of tight trophic linkages, [*Beaugrand and Kirby*, 2010; *Beaugrand et al.*, 2010; *Edwards and Richardson*, 2004]. Mechanisms are complex and tend to be non-linear, with impacts on ecosystems, fisheries and biogeochemical cycles. Climate shifts can also result in abrupt changes or rapid regime shifts in ecosystems [*Alheit*, 2009]. Climate change in the Gulf of Alaska associated with the 1976/77 PDO regime shift produced a very rapid shift in target species for commercial fisheries [*Litzow et al.*, 2008]. A sudden reorganization of commercial fisheries, with attendant social and economic disruption, is a key risk and vulnerability of ongoing climate change in the region.

Alteration of thermal regimes and declining seasonal sea ice could produce changes in high latitude ecosystems that exceed those observed during the climate oscillations of the 20th century. Decreases in seasonal sea-ice in sub-polar regions are *very likely* to lead to increases in the length of the growth season and the intensity of the light available to fuel phytoplankton growth and hence to enhanced primary production and modifications of ecosystem structure [*Arrigo et al.*, 2008]. In the long-term, however, primary production may decrease due to the reduced supply of nutrients to the surface layers. The decline in Arctic sea ice will open dispersal pathways between the North Atlantic and the North Pacific; large numbers of the Pacific diatom *Neodenticula seminae* were found in the North Atlantic in 1999 [*Reid et al.*, 2007]. High latitude sub-regions are also vulnerable to rapid changes in ocean chemistry. There is *medium agreement* that calcifying organisms in these regions will be impacted by ocean acidification with substantial impacts on higher trophic levels although there is *limited evidence* at this point.

30.5.2. Equatorial Upwelling Systems

The largest upwelling systems are found in the equatorial regions of the eastern Pacific and Atlantic oceans (Fig. 30.1). Equatorial Upwelling Systems (EUS) produce a highly productive 'cold tongue' that stretches westward across equatorial areas. The associated upwelling is a consequence of the Earth's rotation and Easterly (westward) winds and currents which drive water northwards and southwards at the northern and southern edges of these sub-regions. As result, cold, nutrient-rich and high CO_2 waters are transported from deep waters into the surface waters, driving high levels of primary productivity which supports 4.7% of total global fisheries productivity (Table 30-1, Figure 30-1). Inter-annual and inter-decadal modes of variability (e.g. ENSO) dominate EUS, particularly in the Pacific [*Barber et al.*, 1994; *Christian and Murtugudde*, 2003; *Le Borgne et al.*, 2002; *McCarthy et al.*, 1996; *Mestas-Nuñez and Miller*, 2006; *Pennington et al.*, 2006; *Signorini et al.*, 1999; *Wang et al.*, 2006b]. Upwelling is reduced during

El Niño years when the trade winds cease, or even reverse, and is strengthened during the strengthened La Niña events. ENSO-periodicity controls primary productivity consequently has a strong influence over associated fisheries production [*Mestas-Nuñez and Miller*, 2006]. ENSO influences the position of the InterTropical Convergence Zone (ITCZ) at the edges of the equatorial upwelling zone and also plays a key role in determining the habitats, productivity, fisheries, and precipitation in these regions.

30.5.2.1. Observed Changes and Potential Impacts

The two EUS show similar behavior and hence are dealt with together in the one section. The average sea temperature associated with the EUS has increased significantly (0.35 and 0.45°C from 1955 to 2005 in the Pacific and Atlantic EUS, respectively; based on data from 1950 to 2009, Table 30-2). Wind speed and cloudiness have decreased in both EUS regions, with the opposite happening along the northern and southern edges (convergence zones) where cloud and wind have increased from 1955 to 2005. In the Pacific, spatial variation in SST is related to frequent El Niño Modoki or Central Pacific El Niño events [*Ashok et al.*, 2007; *Lee and McPhaden*, 2010]. The faster warming of the Atlantic EUS has been associated with a weakening of upwelling [*Tokinaga and Xie*, 2011]. Sea level rise in the eastern equatorial Pacific has been minimal, with the annual rate of change <1 $mm.yr^{-1}$ since 1950 [*Church et al.*, 2006].

Coral reefs in the EUS (e.g. Galápagos and Cocos islands) have relatively low species diversity and poorly developed carbonate reef frameworks in the eastern Pacific, due to the low pH and aragonite saturation of recently-upwelled waters [*Glynn*, 2001; *Manzello*, 2010; *Manzello et al.*, 2008]. Prolonged periods of elevated temperature associated with El Niño have impacted corals, kelps and associated organisms, and induced several possible local extinctions [*Glynn*, 2011]. Since 1985, coral reefs from South America west to the Gilbert Islands of Kiribati have experienced the highest levels of thermal stress [*Donner et al.*, 2010]. In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific [*Baker et al.*, 2008; *Glynn*, 1984]. Subsequent canonical El Niño and Central Pacific El Niño events in 1997/8, 2002/3, 2004/5, and 2009/10 triggered mass coral bleaching by adding to the background increases in sea temperatures due to climate change [*Donner et al.*, 2010; *Obura and Mangubhai*, 2011; *Vargas-Angel et al.*, 2011]. Impacts of El Niño have also interacted with other anthropogenic impacts such as fishing pressure [*Edgar et al.*, 2010] further complicating the attribution of recent ecological changes to climate change.

30.5.2.2. Key Risks and Vulnerabilities

Climate models indicate that ENSO will continue to be a major driver of oceanic variability over the coming century. Consequently, superposition of a warming ocean and future ENSO activity (possibly modified frequency and intensity) may result in oceanic conditions that are different from those experienced during past El Niño and La Niña events [*Power and Smith*, 2007]. Temperatures within equatorial upwelling sub-regions are projected to continue to warm significantly, with temperatures increasing by approximately 0.8°C in the near term (2010-2039), and by approximately 3°C over the long term (2010-2099) under the BAU RCP8.5 scenario (Table 30-2). For Pacific and Atlantic EUS, differences between RCPs become clear beyond mid-century, with warming of SST under RCP2.6 being 0.43°C and 0.46°C to the much higher changes 3.01°C and 3.03°C under RCP8.5, respectively (Table 30-4). These projected increases in sea temperature will cause increasing stress and may largely eliminate key marine ecosystems such as coral reefs from this region (Box 30-1; Figure 30-12), with the temperature associated with these specific ecosystems increasing by more than 3°C by the end of the century. Further increases in atmospheric CO_2 will decrease pH and aragonite saturation of upwelling waters further. These changes in ocean chemistry will impact marine calcifiers, although many of the species from this region have already adapted to the low aragonite and calcite saturation states that result from equatorial upwelling [*Friedrich et al.*, 2012; *Manzello*, 2010]. A substantial risk exists with respect to the synergistic interactions between sea temperature and declining pH, especially as to how they influence a large number of key biological processes (Box CC-OA).

There is a *low confidence* in the current understanding of how (or if) climate change will influence the behavior of ENSO and other long-term climate patterns [*Collins et al.*, 2010], WG1 12.4.4.2). There is also *low agreement*

between different CMIP5 models on how ocean warming will affect ENSO, with no significant change in half the models examined, and both increasing and decreasing activity in others [*Guilyardi et al*., 2012]. These differences appear to be a consequence of the delicate balance within ENSO between dampening and amplifying feedbacks, and the different emphasis given to these processes within the different CMIP5 models [*Collins et al*., 2010]. Other studies have looked at the interaction between the subtropical gyres (STG), EUS, and the warming of surface waters in the Pacific, with at least one study projecting the possible expansion of the STG at the expense of the EUS [*Polovina et al*., 2011]. In the latter case, the area of equatorial upwelling within the North Pacific would decrease by 28%, and primary production and fish catch by 15%, by 2100. Many of the projected changes imply additional impacts on pelagic fisheries due to the migration of fishing grounds deriving from changing distribution of particular sea temperatures [*Bell et al*., 2013a; *Cheung et al*., 2010; *Lehodey et al*., 2008; *Lehodey et al*., 2011; *Lehodey et al*., 2006; *Sumaila et al*., 2011]. These projections suggest that fisheries within EUS will experience increased vulnerability due to elevated variability in space and time as a result of climate change.

30.5.3. Semi-Enclosed Seas

Semi-enclosed seas (SES) represent an subset of ocean sub-regions which are largely land-locked and consequently heavily influenced by surrounding landscapes and climates [*Healy and Harada*, 1991]. In most cases, they support fisheries significant fisheries (3.3% of global production, Table 30-1, Figure 30-1) and opportunities for other industries such as tourism. Five SES (all over 200,000 km^2 with single entrances < 120 km wide) are considered here. This particular geography has reduced circulation and exchange with ocean waters, and water bodies whose jurisdictions are shared by two or more neighbouring states. In many cases, the small volume and disconnected nature of SES (relative to coastal and oceanic environments) makes them highly vulnerable to both local and global stressors, especially with respect to the much reduced options for the migration of organisms as conditions change.

30.5.3.1. Observed Changes and Potential Impacts

30.5.3.1.1. Arabian Gulf

The Arabian Gulf (also referred to as the Persian Gulf), along with Red Sea, is the world's warmest sea with both extreme negative and positive temperature excursions (annual temperature range, 12-35°C). Like other SES, the Arabian Gulf is particularly vulnerable to changing environmental conditions given its landlocked nature. Trends in SST were not significant over the period 1950 to 2009 (Table 30-2) despite a large amount of variability. This may be part of larger regional and abrupt changes that occurred in the late 1980s [*Conversi et al*., 2010]. In keeping with this, recent (1985-2002) localised analyses (e.g. Kuwait Bay) show strong and significant warming trends based, in this case, on AVHRR (NOAA) satellite data of 0.6ºC decade^{-1} [*Al-Rashidi et al*., 2009]. There is *limited evidence* and *limited agreement* as to how this variability influences the marine ecosystems and human activities within the Arabian Gulf, although some ecosystem components (e.g. coral reefs) have been explored to some extent. The mass coral bleaching and mortality associated with 1996 and 1998 was a direct result of the sensitivity of reef-building corals to elevated sea temperatures [*Riegl*, 2002; *Riegl and Piller*, 2003], *high confidence*, Box CC-CR). These changes to coral reefs have resulted in a loss fish species that eat invertebrates while herbivorous and planktivorous fish abundances have increased [*Riegl*, 2002], *medium confidence*). Despite ecosystems there being adapted to some of the highest shallow water temperatures on earth, anthropogenic climate change is driving higher frequencies and intensities of mass coral bleaching and mortality [*Riegl et al*., 2011]. Other biological changes (e.g. harmful algal blooms and fish kills, [*Heil et al*., 2001]) have been associated with the increasing sea temperatures of the Arabian Gulf although attribution to increasing temperatures as opposed to other factors (e.g., water quality) is *uncertain* [*Bauman et al*., 2010; *Sheppard et al*., 2012].

30.5.3.1.2. Red Sea

Few studies have focused on attributing recent changes in the Red Sea to climate change (including ocean acidification). The Red Sea has warmed by 0.74°C from 1982-2006 [*Belkin*, 2009; *Raitsos et al*., 2011] although

trends over the period from 1950-2009 were not significant ($p > 0.05$, Table 30-2) due to a high degree of variability when longer periods are examined (supplementary material, [*Belkin*, 2009]. Regional trends within the Red Sea may also differ with at least one other study reporting higher rates of warming for the Central Red Sea (1.5°C [1950–1997, NOAA Extended Reconstructed SST, ERSST, v3b climatology, [*Cantin et al.*, 2010]. Long-term monitoring of coral community structure and size over 20 years has shown that average coral size has declined [*high confidence*] and species latitudinal limits may have changed [*moderate confidence*]. The decline in average coral size is ascribed to significant heat-mediated bleaching in 1998, and again in 2010 [*Riegl et al.*, 2012]. The patterns of this decline correlate well with the pattern of heating in the Red Sea [*Raitsos et al.*, 2011] with the biggest changes being seen in the southern part of the Red Sea. Skeletal growth of the long-lived massive coral *Diploastrea heliopora* has declined significantly, very likely as a consequence of warming temperatures ($p < 0.05$, *medium confidence*).

Cantin et al. [2010] proposed that corals in the central Red Sea will cease to grow by 2070 (*medium confidence*) although this may not hold for all coral species (e.g. *Porites* and *Cyphastrea*; Cantin et al., in review, PLosOne). For example, an increase in linear extension of *Porites* corals, beginning in the 1980s was recorded in the northern Red Sea [*Heiss*, 1996], where the present local warming rate is ~0.037ºC y^{-1}, suggesting that these corals are living in sub-optimal (cooler waters) conditions and may still benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline as they are in many oceans. *Riegl and Piller* [2003] concluded that coral habitats at moderate depths in the Red Sea might provide important refugia from some aspects of climate change in the future. *Silverman et al.* [2007] quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate system chemistry (pH, aragonite saturation). Their results demonstrate a strong negative impact of ocean acidification on ecosystem scale calcification and decalcification, and that small changes in carbonate dissolution could have large-scale implications for the long-term persistence of carbonate coral reef systems within the Red Sea [*Silverman et al.*, 2007; *Silverman et al.*, 2009].

30.5.3.1.3. Black Sea

The surface waters of the Black Sea have increased by 0.96ºC from 1982 to 2006 [*Belkin*, 2009] which is consistent with other studies [*Bozkurt and Sen*, 2011; *Buongiorno Nardelli et al.*, 2010] *high confidence*). As with other SES, longer data sets do not reveal a significant trend due to large-scale variability prior to 1980 which may be associated with AMO, NAO and other long-term sources of variability (Table 30-2; supplementary material, *Belkin, 2009*). *Buongiorno Nardelli et al.* [2010] observed that short-term SST variability (week-month) is strongly influenced by interactions with the overlying atmosphere, which itself is strongly influenced by the surrounding land temperatures. Freshwater discharge from rivers draining into the Black Sea has remained more or less constant since the early 1960s [*Ludwig et al.*, 2009]. Increased water temperature has steadily eliminated the Cold Intermediate Layer (CIL; with temperatures below 8°C) throughout the Black Sea basin [*Oguz et al.*, 2003], *high confidence*). Reduced water column mixing and upwelling during warmer winter periods has resulted in a reduced supply of nutrients to the upper layers of the Black Sea [*Oguz et al.*, 2003] and expanded areas of low oxygen in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin [*Murray et al.*, 1989], *high confidence*). These changes have coincided with the collapse of fish stocks and the invasion by the ctenophore *Mnemiopsis leidyi* in the 1980s [*Oguz et al.*, 2008], while at the same time, inputs of nutrients such as phosphate from the River Danube have decreased strongly since 1992-1993. Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s [*Oguz and Velikova*, 2010; *Yunev et al.*, 2007]. The Black Sea system is very dynamic and is strongly affected by non-climate stressors in addition to climate change, making attribution of detected trends to climate change difficult.

30.5.3.1.4. Baltic Sea

Temperatures in the highly dynamic Baltic Sea have increased substantially since the early 1980s, with increases of 1.35°C (1982-2006) being among the highest for SES [*Aleksandrov et al.*, 2009; *Belkin*, 2009]). This increase is parallel to the increase in the adjacent North Atlantic driven mainly by AMO. Increases of this magnitude are not seen in longer records throughout the Baltic Sea (1861-2001, [*Mackenzie and Schiedek*, 2007a; b; *Mackenzie et al.*,

2007]; from 1900 to 1998, [*Madsen and Hojerslev*, 2009]). The salinity of the surface and near bottom waters of the Baltic Sea (e.g. Gdansk Basin, [*Aleksandrov et al.*, 2009]; central Baltic [*Fonselius and Valderrama*, 2003; *Mollmann et al.*, 2003] decreased from 1975 to 2000, due to changing rainfall and river run-off and a reduction in the pulses of sea water (vital for oxygenation and related chemical changes) from the North Sea through its opening to the North Sea via Kattegat [*Conley et al.*, 2009; *Hanninen and Vuorinen*, 2011; *Samuelsson*, 1996] high confidence). There is a strong vertical zonation within the Baltic Sea in terms of the availability of oxygen. The shallow sub-regions of the Baltic are relatively well oxygenated. However, oxygen levels are low in the deeper basins, producing conditions where organisms and ecosystems are exposed to prolonged hypoxia.

The annual biomass of phytoplankton has declined almost threefold in the Baltic Transition Zone (Kattegat, Belt Sea) and Western Baltic Sea since 1978. The decrease in phytoplankton abundance and primary productivity since 1978 is very likely to be a response to increasing sea temperature [*Madsen and Hojerslev*, 2009], although the decreased nutrient input to the Danish Straits has almost certainly played a role ([*Henriksen*, 2009] *medium confidence*). Reduced phytoplankton production by increasing sea temperatures is expected to have a negative impact of the productivity of fisheries in the Western Baltic Sea and the transition zone [*Chassot et al.*, 2007]. Decreasing salinity in the Baltic deep basins may also affect zooplankton reproduction, especially of the copepod, *Pseudocalanus acuspes,* contributing to density-dependent decrease in growth of the commercially significant herring and sprat stocks [*Mollmann et al.*, 2003; *Möllmann et al.*, 2005], *high confidence*). The strong relationship between phytoplankton and fish production, and increasing sea temperature, decreasing salinity and other environmental factors, suggests that major changes in fisheries production may occur as sea temperatures increase and the hydrological cycle in the Baltic region is changed (*high confidence*).

A combination of climate-change-induced oceanographic changes (i.e. decreased salinity and increased temperatures) and eutrophication and overfishing have resulted in major structural changes at all trophic levels (particularly, an ecosystem regime shift [*Möllmann et al.*, 2005]) in the deep basins of the Baltic Sea. The strong relationship between primary and secondary production, and oceanography, suggests that major changes in Baltic fisheries production are very likely to occur as temperatures increase and salinities decrease. This has been demonstrated by examples such as that of the commercially important top-predator cod [*Lindegren et al.*, 2010](*medium confidence*).

30.5.3.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and Central Europe. SSTs within the Mediterranean SES have increased 0.43ºC from 1957 to 2008 (supplementary material, *Belkin 2009*) although analysis of data from 1950-2009 does not exhibit a significant trend ($p > 0.05$, Table 30-2) due to large fluctuations of SSTs prior to the 1980s. Increasing SST trends have been reported at a number of monitoring sites in the Mediterranean Sea (e.g. [*Calvo et al.*, 2011; *Coma et al.*, 2009; *Conversi et al.*, 2010]. In the western Mediterranean Sea, water temperatures, over the past 30–40 years, have also increased at depth [*Bethoux et al.*, 1990; *Rixen et al.*, 2005; *Vargas-Yanez et al.*, 2010]. Natural sources of variability such as the AMO and NAO, can obscure or accentuate the overall warming trend [*Marullo et al.*, 2011]. Relatively warm episodes in the 1870–1890s, 1930–1940s and since the 1990s, for example, exhibit an influence of the AMO [*Kerr*, 2000; *Moron*, 2003]. Reported temperature anomalies in the Mediterranean, often locally manifesting themselves as periods of low wind, increased water column stratification and deepening thermocline, are associated with positive phases of the NAO index [*Lejeusne et al.*, 2010; *Molinero et al.*, 2005].

Sea levels have increased rapidly in some areas over the last decades and are also strongly influenced by NAO phases. These rates have been approximately 3.4 $mm.yr^{-1}$ (1990-2009) in the NW Mediterranean [*Calvo et al.*, 2011], *high confidence*). These influences are reduced when measurements are pooled over longer time-scales resulting in a lower rate of sea level rise [*Massuti et al.*, 2008]. If the positive phase of the NAO is more frequent in the future [*Kuzmina et al.*, 2005; *Terray et al.*, 2004], then the future sea level rise may be slightly suppressed due to atmospheric changes [*Jorda et al.*, 2012]. As temperatures have increased, the Mediterranean has become more saline (+0.035 to 0.040 psu over 1950-2000, [*Rixen et al.*, 2005]) and the length of the stratification period persisted twice as long in 2006 than it did in 1974 [*Coma et al.*, 2009].

Conditions within the Mediterranean Sea changed abruptly and synchronously with similar changes across the North, Baltic, and Black Seas in the late 1980s [*Conversi et al*., 2010], which possibly explains the lack of trend in SES Sea surface data when examined over 50-60 years (Table 30-2). These changes in physical conditions (increased temperature, higher sea level pressure, positive NAO index) also coincided with step-changes in the diversity and abundance of zooplankton, decreases in stock abundance of anchovies, and the frequency of red tides and, increases in mucilage outbreaks [*Conversi et al*., 2010]. Mucilage outbreaks are strongly associated with warmer and more stratified water columns (*high confidence*), and lead to a greater abundance and diversity of marine microbes and potentially disease organisms [*Danovaro et al*., 2009]. Increasing temperatures are also driving the northward spread of warm-water species (*medium confidence*) such as the sardine, *Sardinella aurita* [*Sabates et al*., 2006; *Tsikliras*, 2008], and contributed to the fast spread of the coral *Oculina patagonia* [*Serrano et al*., submitted]. The recent spread of warm-water species that have invaded through the Straits of Gibraltar and through the Suez Canal, into cooler northern areas is leading to "tropicalisation" of Mediterranean fauna [*Ben Rais Lasram and Mouillot*, 2008; *Bianchi*, 2007; *CIESM*, 2008; *Galil*, 2008; 2011] (*high confidence*). Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin [*Raitsos et al*., 2010]

In addition to general patterns of warming, periods of extreme temperatures have had large-scale impacts on Mediterranean marine ecosystems. Unprecedented mass mortality events that affected at least 25 prominent invertebrate species occurred during the summers of 1999, 2003 and 2006 across hundreds of kilometres of coastline in the NW Mediterranean Sea [*Calvo et al*., 2011; *Cerrano et al*., 2000; *Crisci et al*., 2011; *Garrabou et al*., 2009] *very high confidence*). Events coincided with either short periods (2-5 days, 2003, 2006) of high sea temperatures (27°C) or longer periods (30-40 days) of modestly high temperatures (24°C, 1999; [*Bensoussan et al*., 2010; *Crisci et al*., 2011]). Impacts on marine organisms have been reported in response to the extreme conditions during events such as those in 1999, 2003 and 2006 in the Mediterranean (e.g. gorgonian-corals mortality [*Coma et al*., 2009], shoot mortality and anomalous flowering of seagrasses [*Diaz-Almela et al*., 2007; *Marba and Duarte*, 2010], *high confidence*). Increasing sea temperatures are very likely to increase the frequency and intensity of these types of heat stress events (*high confidence*).

Long-term data series (over several decades) to measure the rate of acidification in the Mediterranean Sea are scarce [*Durrieu de Madron et al*., 2011]. Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05-0.14 pH units since the preindustrial period [*Luchetta et al*., 2010; *Touratier and Goyet*, 2011], medium confidence). Even the deepest Mediterranean water is contaminated by anthropogenic CO_2, which the greatest relative changes in pH for an entire water column [*Touratier and Goyet*, 2011]. Studies that have explored the impact of ocean acidification on the biology and ecology of the Mediterranean Sea are rare although insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia in Italy [*Hall-Spencer et al*., 2008]. Major changes to Mediterranean organisms and ecosystems were revealed for high CO_2 environments with calcifying organisms (e.g. molluscs, calcareous algae) being negatively affected while seagrasses and some macroalgae appeared to benefit.

30.5.3.2. Key Risks and Vulnerabilities

SES are highly vulnerable to changes in global temperature on account of their small volume and landlocked nature. Consequently, SES are *virtually certain* to respond faster than other parts of the ocean (*high confidence*). Risks to ecosystems within SES are *very likely* to increase as water columns become further stratified under increased warming, promoting hypoxia at depth and reducing nutrient supply to the upper water column (*medium evidence, high agreement*). The impact of rising temperatures on SES is exacerbated by their vulnerability to other human impacts such as overexploitation, pollution and enhanced run-off from modified coastlines. Due to a mixture of global and local human stressors, key fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years. A major risk exists for SES from projected increases in the frequency of temperature extremes that drive mass mortality events, increasing water column stabilisation leading to reduced mixing, and resulting changes to the distribution and abundance of marine organisms. The vulnerability of marine

ecosystems, fisheries and human communities associated with the SES will continue to increase as global temperatures increase.

There is *very high confidence* that sea temperatures within the five SES will increase further under even moderate Representative Concentration Pathways (RCP). Under BAU (RCP 8.5; Table 30-4), sea temperatures in the SES are projected to increase by 0.93-1.24°C by 2039 and by 3.45-4.37°C by the end of the century (Table 30-4). The greatest increases are projected for the surface waters of the Baltic Sea (4.26°C) and Arabian Gulf (4.33°C), with lower yet substantial amounts of warming in the Red Sea (3.45°C). The heat content added to these small oceans is *very likely* to increase stratification of the water column, which will reduce the nutrient supply to the upper layers of the water column, reducing primary productivity and driving major changes to the structure and productivity of fisheries. Reduced mixing and ventilation, along with increased microbial metabolism, will *very likely* expand hypoxia and increase the size and number of 'dead zones'. Changing rainfall intensity is likely to also have strong influences on the physical and chemical conditions within SES, in some cases combining with climate change to transform these areas. These changes are likely to increase the risk of reduced O_2 levels to Baltic and Black Sea ecosystems, which is *very likely* to affect fisheries. Based on responses to temperature extremes seen over the past 30 years, these changes will increase the frequency and intensity of impacts arising from heat stress, such as the mass mortality of benthic organisms in the Mediterranean during the summers of 1999, 2003 and 2006, and the Arabian Gulf in 1996 and 1998. Similar projections to those seen in 30.8.4 can be applied to the coral reefs of the Arabian Gulf and the Red Sea, where temperatures are *very likely* to increase above established thresholds for mass coral bleaching and mortality (*high confidence*; Figure 30-12).

30.5.4. Coastal Boundary Systems

The Coastal Boundary Systems (CBS) are highly productive regions, comprising 10.6% of primary production and 28.0% of global fisheries production (Table 30-1, Figure 30-1). CBS regions are also bounded by the sub-regions of the Pacific, Atlantic and Indian oceans, except in coastal areas associated with the EBUEs. Within these sub-regions, the CBSs are dominated by powerful currents such as the Kuroshio (Pacific) and the Gulf Stream (Atlantic), and are strongly influenced by monsoons (e.g. Asian-Australian and African monsoons). The CBS includes the marginal seas of the NW Pacific, Indian, Atlantic and comprises Bohai/Yellow Sea, East China Sea, South China Sea and South-east Asia seas (e.g. The Timor, Arafura, Sulu, and northern coast of Australia) in the Pacific, and the Arabian Sea, Somali Current system, East Africa coast, small archipelagic states, Mozambique Channel and Madagascar in the Indian Ocean, and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean.

30.5.4.1. Observed Changes and Potential Impacts

Many ecosystems within the CBS are strongly affected by the local activities of often dense coastal human populations. Activities such as the overexploitation of fisheries, unsustainable coastal development and pollution have resulted in the wide-spread degradation of CBS ecosystems [*Burke et al*., 2002; *Burke et al*., 2011]. These influences have combined with steadily increasing ocean temperature and acidity to drive major changes to a range of important ecosystems over the past 50 years. Understanding the interactions between climate change and non-climate change drivers is a central part of the detection and attribution process within the CBS.

Overall, CBSs have warmed by 0.46-0.67°C from 1955 to 2005 (Table 30-2), although changes within the Gulf of Mexico/Caribbean sub-region were not significant over this period. Key sub-regions within the CBS such as Coral Triangle and Western Indian Ocean have warmed by 0.65 and 0.50°C respectively from 1955-2005 (calculated using data from 1950-2009, Table 30-2). Rates of sea level rise vary from low (2-3 mm $year^{-1}$, Caribbean) to very high rates (10 mm $year^{-1}$, SE Asia; 30.3.1.2). Ocean acidification also varies from region to region, influenced by oceanographic and coastal processes (Figure 30-6 A-D, Figure 30-7) which often have a large human component.

30.4.4.1.1. Bohai/Yellow Sea/East China Sea

Bohai/Yellow Sea and East China Sea (ECS) are shallow marginal seas along the edge of the NW Pacific that are strongly influenced by Kuroshio, the East Asian Monsoon (EAM), and major rivers such as Yellow River and Changjiang (Yanktze) River. The Kuroshio intrusion influences the associated marginal seas [*Matsuno et al*., 2009], providing abundant nutrients which support high levels of primary productivity [*Chen et al*., 1996; *Wong et al*., 2001; *Wong et al*., 2000]. The ecosystems of the ECS are heavily impacted by anthropogenic pressure factors (e.g., overfishing and pollution) which tend to compound the impacts of climate change.

SST within the ECS increased rapidly since the early 1980s [*Cai et al*., 2011.; *Jung*, 2008; *Lin et al*., 2005; *Tian et al*., 2012]. The largest increases in SST have occurred in the ECS in winter (1.96°C, 1955-2005) and Yellow Sea in summer (1.10°C, 1971-2006 [*Cai et al*., 2011.]. These changes in SST are closely linked to the weakening of the EAM (e.g. [*Cai et al*., 2011.; *Cai*, 2006.; *Tang et al*., 2009], and increasing warmth of the Kuroshio Current [*Qi*, 2010; *Wu et al*., 2012; *Zhang et al*., 2011]. At the same time, dissolved oxygen has decreased [*Jung*, 2008; *Lin et al*., 2005; *Qi*, 2010] with an associated increase in the size of the hypoxic areas (≤60 mmol kg^{-1}) in coastal areas of Yellow Sea/ECS [*Jung*, 2008; *Ning et al*., 2011; *Tang*, 2009].

There is *robust evidence* and *high agreement* that primary productivity, biomass yields and fish capture rates are declining within the ECS [*Lin et al*., 2005; *Tang*, 2009; *Tang et al*., 2003]. There is *medium evidence and medium agreement* that these are being driven by climate change and human pressures. Warm-water zooplankton species have expanded northward in the Changjiang River Estuary as water temperatures have increased [*Ma et al*., 2009]. Fluctuations in herring abundance also appear to closely track SST regime shifts within the Yellow Sea [*Tang*, 2009]. The proportion of warm water species relative to warm temperate species from plankton to fish species in the Changjiang River Estuary (extending to the south Taiwan Strait) have changed in the past decades [*Lin and Yang*, 2011; *Ma et al*., 2009; *Zhang et al*., 2005]. Meanwhile, the frequency of harmful algal blooms (HAB) and blooms of the Giant Jellyfish (*Nemopile manomurai*) in the offshore area of ECS have increased and have been associated with ocean warming and other factors such as eutrophication [*Cai and Tan*, 2010; *Tang*, 2009; *Ye and Huang*, 2003]. While attribution of these changes to anthropogenic climate change is complicated by the increasing influence of non-climate related human activities, many of these changes are consistent with those expected as sea temperatures increase.

30.5.4.1.2. South China Sea

The South China Sea (SCS) is surrounded by continental areas and a large number of islands, and is connected to the Pacific, ECS, and Sulu Sea by straits such as the Luzon and Taiwan Strait. The region is greatly influenced by cyclones/typhoons, and by the Pearl, Red and Mekong Rivers. The region has a distinct seasonal circulation and is greatly influenced by the southwest monsoon (in summer), the Kuroshio Current and northeast monsoon (in winter). The SCS includes significant commercial fisheries areas and includes coral reefs, mangroves and seagrasses.

The surface waters of the SCS have been warming steadily from 1945-1999 [*Li et al*., 2002; *Liu et al*., 2007] with the annual mean SST in the central SCS increasing by 0.92°C (1950-2006) [*Cai et al*., 2008,], a rate similar to that observed for the entire Pacific CBS from 1955-2005 (calculated using data from 1950-2009, 0.67°C, Table 30-2). Significant freshening in the SCS intermediate layer since the 1960s has been observed [*Liu et al*., 2007]. The temperature change of the upper layers of the SCS has made a significant contribution to sea level variation which is spatially non-homogeneous and varies in time [*Cheng and Qi*, 2007; *Li et al*., 2002].

Identifying a clear climate change impact within the SCS is difficult due to complexity of other factors and their interactions (e.g. local human stressors, and 'natural' climate variability such as EAM, ENSO and PDO). There is *limited evidence* and *medium agreement*, however, that changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries and the size of demersal trawl catches in northern SCS [*Ning et al*., 2008]. Coral reefs and mangroves are degrading rapidly as a result of both climate change and non-climate change factors (Box CC-CR)[*China-SNAP*, 2011]. Elevated SSTs have triggered mass coral bleaching and mortality of coral reefs within the SCS in 1998 and 2007 [*Li et al*., 2011; *Yu et al*., 2006]. On the other hand, warming of

ocean waters has very likely favourably influenced the establishment of a high latitude, non-carbonate coral community in Daya Bay in the northern SCS, although this community has recently degraded due to local anthropogenic stresses [*Chen et al*., 2009; *Qiu et al*., 2010].

30.5.4.1.3. Southeast Asian seas

The South-east Asian Seas (SASs) have a complex island and archipelago domain which interacts with the westward flow of the North Equatorial current and the Indonesian through-flow (Figure 30-1). A large part of this region is referred to as the 'Coral Triangle' [*Veron et al*., 2009] and is the world's most biologically diverse marine area and includes parts of Malaysia, Indonesia, Philippines, Timor L'este, Solomon Islands, and Papua and New Guinea. Sea temperatures increased significantly over the period 1985-2006 [*McLeod et al*., 2010; *Peñaflor et al*., 2009] although with considerable spatial variation. Trends examined over longer periods (1955-2005) also show significant warming (+0.65°C, $p < 0.05$; Table 30-2, calculating using data from 1950-2009). Sea level is increasing by 10 $mm.yr^{-1}$ in a significant proportion of this region [*Church et al*., 2006; *Church et al*., 2004; *Green et al*., 2010]. Like other tropical areas in the world, coral reefs within SASs have experienced periods of elevated temperatures which have driven several mass coral bleaching and mortality events since the early 1980s (Figure 30-12), with the most recent occurred during the warm conditions associated with 2010 [*Krishnan et al*., 2011; *McLeod et al*., 2010]. There is *robust evidence* and *high agreement* that these changes are the result of increasing ocean temperatures and are very likely to be a consequence of anthropogenic climate change (*high confidence*, Box CC-CR; WG1 10.4.1). Calcification rates of some key organisms (e.g., reef-building corals [*Tanzil et al*., 2009] have slowed over the past two decades with increased sea temperature although the cause remains uncertain due to the possible influence of ocean acidification in these changes. While a large part of the decline in coral reefs has been due to rising local stresses (principally destructive fishing, declining water quality, and overexploitation of key reef species), there is high agreement that projected increases in SST represent a major challenge for these valuable ecosystems [*Burke and Maidens*, 2004; *Burke et al*., 2002].

30.5.4.1.4. Arabian Sea and Somali Current

The Arabian Sea and Somali current are relatively productive ocean areas, being strongly influenced by upwelling and the monsoonal system. Wind-generated upwelling enhances primary production in the western Arabian Sea [*Prakash and Ramesh*, 2007]. Several key fisheries within this region are under escalating pressure from both fishing and climate change. Sea water temperature has increased by 0.18ºC and 0.26ºC in the Arabian Sea and Somali current, respectively, over the period 1982-2006 (HadSST2, [*Belkin*, 2009; *Rayner et al*., 2003], which is consistent with the overall rate of warming of the Western Indian Ocean portion of the CBS from 1955-2005 (0.50ºC, using data from 1950-2009, Table 30-2). Salinity of surface waters in the Arabian Sea has also increased by 0.5-1.0% over the past 60 years (Figure 30-6D) due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf.

The aragonite saturation horizon in the Arabian Sea and Bay of Bengal is now 100 to 200 m shallower than it was in preindustrial times as a result of ocean acidification [*Feely et al*., 2004]. More than 50% of oxygen minimum zones (OMZs) and dead zones in the world oceans [*Diaz and Rosenberg*, 2008] occur in the Arabian Sea (Figure 30-8) and Bay of Bengal [*Helly and Levin*, 2004] where, unlike other sub-regions, OMZs have not expanded since the 1960s [*Karstensen et al*., 2008]. As in other tropical sub-regions, increasing sea temperatures have increased the frequency of mass coral bleaching and mortality within this region [*Goreau et al*., 2000; *Wilkinson*, 2004; *Wilkinson and Hodgson*, 1999]. Shoaling of the aragonite saturation horizon is likely to affect a range of organisms and processes, such as the depth distribution of pteropods in the western Arabian Sea [*Hitchcock et al*., 2002; *Mohan et al*., 2006]. The information regarding the impacts of climate change within this region is undeveloped and suggests that important physical, chemical and biological responses to climate change need to be the focus of further investigation.

30.5.4.1.5. East Africa coast and Madagascar

Oceanic conditions within the East Africa and Madagascar region influence on the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagos (Comores, Mauritius and the Seychelles). Like the north-west section of the Indian Ocean, sea temperatures are increasing rapidly (*high confidence*, $p < 0.05$). Changes in surface salinity vary with the location along the East African coastline. Periods of heat stress over the past 20 years has triggered mass coral bleaching and mortality on coral reef ecosystems with within this region [*Ateweberhan and McClanahan*, 2010; *Ateweberhan et al*., 2011; *McClanahan et al*., 2009a; *McClanahan et al*., 2009b; *McClanahan et al*., 2009c; *McClanahan et al*., 2007]. Steadily increasing sea temperatures have also produced anomalous growth rates in long-lived corals such as *Porites* (*high confidence,* $p < 0.05$)[*McClanahan et al*., 2009b]. Differences in the susceptibility of reef-building corals to stress from rising sea temperatures has also resulted in changes to the composition of coral (*high confidence,* $p < 0.05$, [*McClanahan et al*., 2007] and benthic fish communities (*high confidence*, $p < 0.05$, [*Graham et al*., 2008; *Pratchett et al*., 2011a], which is *very likely* to alter species composition and potentially the productivity of coastal fisheries (*robust evidence, high agreement*, *high confidence*)[*Jury et al*., 2010], although there may be a significant lag between the loss of coral communities and the subsequent changes in the abundance and community structure of fish ($p < 0.05$, [*Graham et al*., 2007]. Attempts to slow these impacts have included the establishment of marine protected areas and changes to fishing management [*Cinner et al*., 2009; *Jury et al*., 2010; *MacNeil et al*., 2010; *McClanahan et al*., 2008].

30.5.4.1.6. Gulf of Mexico and Caribbean Sea

The Caribbean Sea and the Gulf of Mexico form a semi-contained maritime province within the Western Atlantic. These areas are dominated by a range of activities including mineral extraction, fishing and tourism which provide employment and opportunity for over 100 million people who live in coastal areas of the US, Mexico and a range of other Caribbean nations [*Adams et al*., 2004]. The Caribbean Sea and the Gulf of Mexico have warmed by 0.50°C and 0.31°C respectively from 1982 to 2006 [*Belkin*, 2009; *Sherman et al*., 2009]. Warming trends are not significant from 1950-2009 (Table 30-2) which may be partly due to warming being spatially heterogeneous and the enclosed nature of this region making it strongly influenced by long-term variability in a similar way to that seen with respect to the SES sub-regions (30.5.3.1). The Caribbean region has experienced a sustained decrease in the aragonite saturation state from 1996 to 2006 [*Gledhill et al*., 2008]. Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2-3 mm y^{-1} from 1950 to 2000 [*Church et al*., 2004; *Zervas*, 2009].

Understanding influences of climate change on ocean ecosystems in this region is complicated by confounding influence of growing human populations and activities. The recent expansion of the seasonal hypoxic zone has been attributed to nitrogen inputs driven by land management [*Donner et al*., 2004; *Turner and Rabalais*, 1994] and changes to river flows, wind patterns, and thermal stratification of Gulf waters, which are likely to increase the size of the Gulf of Mexico "dead zone" [*Justic et al*., 1996; *Justic et al*., 2007; *Levin et al*., 2009; *Rabalais et al*., 2009; *Rabalais et al*., 2010]. Coastal pollution and fishing have also had increasing impacts that have potentially interacted with the influence of climate change on ocean ecosystems within this region (WGII's Ch5, Ch29).

A combination of local and global disturbances has driven the large-scale loss of reef-building corals across the Caribbean Sea since the late 1970s [*Gardner et al*., 2003; *Hughes*, 1994]. Record thermal stress in 2005 triggered the largest mass coral bleaching and mortality event on record for the region, damaging coral reefs across hundreds of km^2 in the eastern Caribbean Sea [*Donner et al*., 2007; *Eakin et al*., 2010]. Similar conditions and impacts on coral reefs occurred in 2010. Increasing sea temperatures has also been implicated in the spread of disease organisms in the Caribbean [*Harvell et al*., 2002b; *Harvell et al*., 1999; *Harvell et al*., 2004] and some introduced species [*Firth et al*., 2011]. As in other sub-regions, pelagic fish species are sensitive to changes in sea temperature and modify their distribution and abundance [*Muhling et al*., 2011]. Ocean acidification may also be altering patterns of fish recruitment although direct evidence for impacts on Caribbean species is lacking [*Dixson et al*., 2010; *Dixson et al*., 2008; *Munday et al*., 2009].

30.5.4.2. Key Risks and Vulnerabilities

At least 850 million people live within 100 km of CBS regions (i.e. number living within 100 km of coral reefs is 850 million and is therefore a minimum estimate given there are other ecosystems other than coral reefs, *Burke et al.* [2011]) from where they derive a range of benefits from food, coastal protection, cultural services, and income from industries such as fishing and tourism. Marine ecosystems within the CBS are sensitive to increasing sea temperatures (Figure 30-12), although detection and attribution is complicated by the significant influence and interaction with non-climate change stressors (water quality, over-exploitations of fisheries, coastal degradation; Box CC-CR). Warming is *likely* to have changed the primary productivity of ocean waters, placing valuable ecosystems and fisheries at risk within the ECS. Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of CBS. Given the impact on coastal ecosystems and fisheries, these changes are *very likely* to increase the vulnerability of coastal communities throughout the CBS.

Sea temperatures are rapidly increasing within many parts of the CBS ecosystems, which will continue over the next few decades and century. Sea temperatures are projected to change by 0.34-0.50°C in the near–term (by 2039) and by 0.23 - 0.74°C in the long –term (by 2099) under the lowest RCP scenario (RCP2.6). Under BAU RCP8.5, CBS sea temperatures are projected to increase 0.62-0.85°C by 2039 and 2.44 – 3.32°C by 2099 (Table 30-4). Given the large-scale impacts (e.g. mass coral bleaching and mortality events) have occurred in response to much smaller changes in the past over the CBS regions (0.10-0.67°C from 1955 to 2005, Table 30-2), the projected changes of 2.44 – 3.32°C by 2099 are *very likely* to have large-scale and negative impacts on structure and function of many CBS ecosystems (Figure 30-12). It is *virtually certain* that fishery composition will change with *robust evidence* and *high agreement* that catch rates and productivity of many fisheries will be *very likely* to decrease as waters warm, acidify and stratify, and as crucial habitat associated with ecosystems such as coral reefs degrades. These changes are *very likely* to increase the vulnerability of millions of people who live in coastal communities and depend directly on fisheries and other ecological goods and services.

It is *very likely* that coral reef ecosystems will not survive changes in sea temperature beyond an additional increase of 1°C (Box CC-CR; Figure 30-12). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle sub-regions [*Hoegh-Guldberg*, 1999; *Strong et al.*, 1997; *Strong et al.*, 2011], with the exposure to higher temperatures that are projected under medium (RCP4.5) to high (RCP8.5) scenarios, reveals that both coral reef rich regions are *virtually certain* to experience levels of thermal stress that cause coral bleaching every 1-2 years by the mid to late part of this century (*robust evidence, high levels of agreement, very high confidence,* Figure 30-5 A,B; Figure 30-12A,B). The frequency of mass mortality events (DHM > 5; Figure 30-11 A,C) climbs towards events that occur every 1-2 years by mid to late of this century under low to high climate change scenarios (*robust evidence, high levels of agreement, very high confidence,* [*Donner et al.*, 2005; *Frieler et al.*, 2012; *Hoegh-Guldberg*, 1999]. Mass mortality events that impact coral reefs will result in changes to community composition in the short-term (2010-2039)[*Adjeroud et al.*, 2009; *Berumen and Pratchett*, 2006] and a continuing downward trend in reef-building coral stocks in the longer term [*Baker et al.*, 2008; *Bruno and Selig*, 2007; *Gardner et al.*, 2003].

[INSERT FIGURE 30-12 HERE
Figure 30-12: Annual maximum proportions of reef pixels with Degree Heating Months (Donner et al. 2007; DHM) ≥ 1 (coral bleaching) and DHM ≥ 5 (bleaching across 100% of affected areas with significant mortality, Eakin et al. 2010) for each of the six coral regions (Figure 30-3) have been depicted as bar graphs for the period 1870-2009. This part of the graph is derived from the HadISST 1.1 data set. The black line plotted on top of the bar graphs is the maximum annual area value for each decade over the period 1870-2009. This value is continued through 2010-2099 using CMIP-5 data and splits into the four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0 and 8.5). DHMs were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHMs the annual percentage of grid cells with DHM ≥ 1 and DHM ≥ 5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010-2099 are the average of these maximum proportion values for each RCP. Monthly SST anomalies are derived using a 1985-2000 maximum monthly mean (MMM) climatology derived in the calculations for Figure 30-4. This was done separately for HadISST 1.1 and each of the CMIP-5 models and each of the four RCPs, at each grid cell for each region. DHMs are then derived by adding up the monthly anomalies using a 4 month rolling sum.]

30.5.5. Eastern Boundary Upwelling Ecosystems

The Eastern Boundary Upwelling Ecosystems (EBUE) includes the California, Peru/Humboldt, Canary/NW Africa, and Benguela. They are highly productive sub-regions involving primary productivity that may exceed 1,000 g C m^{-2} y^{-1}. Although these provinces comprise <2% of the world ocean area, they contribute nearly 7% of marine primary production (Table 30-1, Figure 30-1) and more than 20% of the world's capture fisheries [*Pauly and Christensen*, 1995], which are dominated by planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous benthic-fish such as hake. This level of productivity is a result of large-scale atmospheric pressure gradients and wind systems which advect surface waters offshore (Box 30-1), which are then replaced with cold, nutrient-rich waters upwelled from depth into coastal euphotic zones [*Chavez*, 2011; *Chavez and Messie*, 2009; *Chavez et al.*, 2011]. At the same time, upwelling waters also have high concentrations of CO_2 as well as low pH and reduced concentrations of oxygen, trends that are likely to increase as atmospheric CO_2 increases [*Feely et al.*, 2008; *Gruber*, 2011]. Nutrient input stimulates primary production from phytoplankton blooms that are transferred to mid and upper trophic levels, resulting in substantial fish, seabird and marine mammal populations. As a result, EBUEs are considered "hotspots" of biodiversity [*Block et al.*, 2011].

30.5.5.1. Observed Changes and Potential Impacts

The historical importance of EBUE fisheries has resulted in extensive studies of their coupled climate-ecosystem dynamics (e.g. California Current). Decadal variability poses challenges to the detection and attribution of changes within the EBUEs to climate change although there are a number of long-term studies that have been able to provide insight into the patterns of change and their causes. Like other ocean sub-regions, EBUEs are projected to warm under climate change, experiencing increased stratification as well as periods of intensified upwelling, and altered wind fields as westerly winds shift polewards. However, cooling is also predicted for some EBUEs, resulting from the intensification of wind-driven upwelling [*Bakun*, 1990]. There is *limited* agreement on a broad response by EBUEs to climate change over past decades with considerable variability in warming and cooling both within and among systems [*Burrows et al.*, 2011; *Demarcq*, 2009], see 30.3.1.1 Table 30-2). The California and Canary Currents have warmed by 0.61 and 0.45°C ($p \leq 0.05$, 1950-2009; Table 30-2) respectively, while there has been no significant change in the temperature of the surface waters of the Benguela and Humboldt Currents since from 1950-2009 ($p > 0.05$, Table 30-2). These trends match shorter term trends (or lack of trends) for EBUs using Pathfinder version 5 data (Table 1, [*Demarcq*, 2009]. These differences between EBUEs are *likely* to be the result of differences in the influence of long-term variability and the specific responses of coastal wind systems to warming (Figure 30-6A) although an analysis of wind data over the same period did not pick up clear trends [*Demarcq*, 2009].

How climate change is likely to influence ocean upwelling is central to resolving ecosystem and fishery responses within each EBUE. There is considerable debate, however, as to whether or not climate change will drive an intensification of upwelling (e.g. [*Bakun et al.*, 2010; *Narayan et al.*, 2010]) in all regions. Discussion of the various hypotheses for how climate change is likely to affect coastal upwelling is presented in Box 30-1. EBUEs are also areas of naturally low pH and high CO_2 concentrations due to upwelling, and consequently may be vulnerable to ocean acidification and its synergistic impacts. A full understanding of the impacts of ocean acidification is discussed elsewhere (Box CC-OA; 6.2.2, 6.3.4, [*Kroeker et al.*, 2013], WG1 6.4).

30.5.5.1.1. Canary Current

Part of the North Atlantic STG, the Canary Current extends from northern Morocco southwestward to the North Atlantic Equatorial Current. It is linked with the Portugal Current (which is sometimes considered part of the Canary Current) upstream and extends downstream to the Atlantic Equatorial Current. The coastal upwelling system, however, is limited to a narrow belt along the Saharan west coast to the coast of Guinea, with the most intense upwelling centrally, along the coast of Mauretania (15-20ºN) and Morocco (21-26°N). Total fish catches, comprising mainly coastal pelagic sardines, sardinellas, anchovies and mackerel, have fluctuated around 2 million

tons.yr^{-1} since the 1970s (http://www.seaaroundus.org/lme/27.aspx). Contrasting with the other EBUEs, fishing productivity is modest, probably due to the legacy of uncontrolled fishing in the 1960s [*Arístegui et al.*, 2009].

Most observations suggest that the Canary current is warming at both local [*Demarcq*, 2009] and regional [*Belkin*, 2009] scales since the early 1980s with analysis of HadSST 1.1 data from 1950-2009 indicating warming of 0.45°C from 1955 to 2005 ($p<0.05$; Table 30-2) with a 20% and 45% decrease in the strength of upwelling in winter and summer respectively from 1967 to 2006 [*Gómez-Gesteira et al.*, 2008]. This is consistent with a decrease in wind strength over the past 60 years (Figure 30-6A), which reduces the upwelling and nutrient concentrations, and the supply of iron-laden dust from the Sahara [*Alonso-Pérez et al.*, 2011]. There is *medium evidence* and *agreement* that primary production in the Canary Current has decreased over the past two decades [*Arístegui et al.*, 2009; *Demarcq*, 2009], Table 1) contrasting trends apparent of nearby region of NW Spain [*Bode et al.*, 2011]. Satellite chlorophyll records (SeaWifs, MODIS) are relatively short, making it difficult to distinguish longer-term patterns of variability from the influence of climate change (*low confidence*)[*Henson et al.*, 2010]. There is also substantial interannual to decadal-scale variability in the fish catches in this system, and catch trends (1950-2007), which is not entirely consistent with these patterns of change in temperature, upwelling, or nutrient supply [*Arístegui et al.*, 2009; *Zeeberg et al.*, 2008].

30.5.5.1.2. Benguela Current

The Benguela Current originates from the eastward-flowing, cold South Atlantic Current, flows northward along the African southwest coast, and is bounded north and south by the warm-water Angola and Agulhas Currents, respectively. Upwelling is strongest and most persistent toward the center of the system in the Lüderitz-Orange River upwelling cell [*Hutchings et al.*, 2009]. Fish catch reached a peak in the late 1970s at 2.8 million tons.yr^{-1} (http://www.seaaroundus.org/lme/29/1.aspx), before declining to around 1 million tons.yr^{-1} (present) as a combined result of overfishing and inter-decadal environmental variability [*Cury and Shannon*, 2004; *Heymans et al.*, 2004; *Hutchings et al.*, 2009]. Commercial fisheries currently comprise sardine, anchovy and horse mackerel, and hake.

Most research in the Benguela Current has focused on fisheries and oceanography, with little emphasis on climate change. As with the other EBUEs, strong inter-annual and inter-decadal variability in physical oceanography make the detection and attribution of biophysical trends to climate change difficult. Nevertheless, physical conditions of the Benguela are highly sensitive to climate variability over a range of scales, and especially to atmospheric teleconnections that alter local wind stress [*Hutchings et al.*, 2009; *Leduc et al.*, 2010; *Richter et al.*, 2010; *Rouault et al.*, 2010]). Consequently, there is *medium agreement* that the Benguela system will change as a result of climate change [*Demarcq*, 2009].

There is no significant trend in the temperature of the surface waters of the Benguela Current from 1950 to 2009 ($p > 0.05$; Table 30-2) although shorter records show a decrease in the temperature of the south-central Benguela (0.35–0.55 ºC.decade^{-1} [*Rouault et al.*, 2010] or the whole Benguela region (total decrease of 0.24ºC, *Belkin* [2009]). These differences between short versus long records indicate the substantial influence of long-term variability on the Benguela system, reflected by the index of variability shown in Table 30-2. Information on other potential climate-change impacts within the Benguela is sparse. Sea-level rise is similar to the global mean, although it has not been measured rigorously within the Benguela [*Veitch*, 2007]. Although upwelling water in the northern and southern portions of the Benguela exhibits elevated and suppressed pCO_2, respectively [*Santana-Casiano et al.*, 2009]), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, while periodic hypoxic events in the Benguela are driven largely by natural advective processes, these may be exacerbated by future climate change [*Bakun et al.*, 2010; *Monteiro et al.*, 2008].

Despite its apparent sensitivity to environmental variability, there is no published evidence from the Benguela EBUE that attributes marine ecological impacts to climate change with any degree of confidence [*Poloczanska et al.*, 2013]. For example, pelagic fish [*Roy et al.*, 2007], benthic crustaceans [*Cockcroft et al.*, 2008] and seabirds [*Crawford et al.*, 2008] have demonstrated general eastward range shifts around the Cape of Good Hope. Although these may be associated with increased upwelling along the South African south coast, specific studies that attribute these changes to anthropogenic climate change are lacking.

30.5.5.1.3. California Current

The California Current spans ~23° of latitude from central Baja California, Mexico, to central British Columbia, linking the North Pacific Current (Westwind Drift) with the North Equatorial and Kuroshio currents, to form the North Pacific Gyre. High productivity driven by advective transport and upwelling [*Checkley and Barth*, 2009; *Chelton et al.*, 1982; *Hickey*, 1979] supports well-studied ecosystems and fisheries. Fish catch data from the California Current since 1950 is about 0.6 million tons.yr^{-1} (http://www.seaaroundus.org/lme/3.aspx) which makes it the lowest catch of the four EBUEs. However, a major fraction of the catches is on one higher trophic level than in the other EBUEs, i.e. more on piscivores than planktivores. Sardine (~47,000 metric tons.yr^{-1}) and squid (~65,000 metric tons.yr^{-1}) dominated the commercial catch of lower trophic level fisheries in the California Current (2000-2009) while anchovy contributed only ~10,000 metric tons.yr^{-1}. Further north, Pacific Hake and salmonids dominate the higher trophic-level fisheries. The ecosystem supports the foraging and reproductive activities of 2-6 million seabirds from around 100 species [*Briggs and Chu*, 1987]. Marine mammals are diverse and relatively abundant, including recovering populations of Humpback whales, among others [*Barlow et al.*, 2008].

The average temperature of the California Current has warmed by 0.61°C from 1955 to 2005 (1.1, $p < 0.05$, Table 30-2) and from 0.14 to 0.80 ºC (1985-2007, [*Demarcq*, 2009]. Like other EBUEs, the California Current is characterised by large-scale inter-annual and inter-decadal climate-ecosystem variability [*Chavez et al.*, 2003; *Checkley and Barth*, 2009; *Hare and Mantua*, 2000; *McGowan et al.*, 1998]. During an El Niño, coastally-trapped Kelvin waves from the tropics deepen the thermocline, thereby severely reducing upwelling and increasing ocean temperatures from California to Washington [*King et al.*, 2011]. Atmospheric teleconnections to the tropical Pacific alter wind stress and coastal upwelling. Therefore, the ENSO is intimately linked with Bakun's (1990) upwelling intensification hypothesis (Box 30-1). Inter-decadal variability in the California Current stems from variability in the Pacific-North America pattern [*Overland et al.*, 2010], which is influenced by the PDO [*Mantua et al.*, 1997] and the NPGO [*Di Lorenzo et al.*, 2008]. The major effects of the PDO and NPGO appear north of 39°N [*Di Lorenzo et al.*, 2008; *Menge et al.*, 2009].

Increasing upwelling has implications for productivity which is driven primarily by "bottom-up" trophic mechanisms [*Fleeger et al.*, 2006; *Ware and Thomson*, 2005], with upwelling, transport, and chlorophyll concentrations showing strong interannual couplings. These, in turn, influence trophic transfer up the food chain, affecting zooplankton [*Hooff and Peterson*, 2006; *Keister et al.*, 2011], forage fish [*Brodeur et al.*, 2008], seabirds [*Abraham and Sydeman*, 2004; *Ainley et al.*, 1995], and marine mammals [*Barlow et al.*, 2008; *Thompson et al.*, 2012]. Ecosystem dynamics are therefore sensitive to and may be strongly masked or accentuated by natural variability. For instance, the distribution for many species of larval fish in the Californian Current is strongly related to natural variability. However, many species are also moving polewards over long time-spans, an observation which is consistent with observed warming in the region [*Hsieh et al.*, 2009].

There is *robust evidence* that the California Current has experienced a decrease in the number of upwelling events (23-40%) while the duration of each upwelling event has increased such that the overall magnitude of upwelling events has increased from 1967 to 2010 [*Iles et al.*, 2012], which is consistent with changes expected under climate change [*Iles et al.*, 2012]. Oxygen concentrations have also undergone large and consistent decreases from 1984-2006 throughout the California current, with the largest relative decreases occurring below the thermocline (21% at 300 m). The hypoxic boundary layer ($\leq$60 mmol kg^{-1}) has also shoaled up to 90 m in some regions [*Bograd et al.*, 2008]. These changes are consistent with the increased input of organic carbon into deeper layers from enhanced productivity, which stimulates microbial activity and results in the drawdown of oxygen [*Bakun et al.*, 2010]. These changes are likely to reduce the available habitat for key benthic communities as well as fish and other mobile species [*Stramma et al.*, 2012]. Increasing microbial activity will also increase the partial pressure of CO_2, decreasing pH and the carbonate chemistry of seawater. Together with the shoaling of the saturation horizon, these changes have increased the incidence of undersaturated, low pH and corrosive water flowing onto portions of the continental shelf (40-120 m, [*Feely et al.*, 2008] with consequences for industries such as the shellfish aquaculture industry [*Barton et al.*, 2012].

30.5.5.1.4. Humboldt Current

The Humboldt Current is the largest of the four EBUEs, covering an area larger than the other three combined. It comprises the eastern edge of South Pacific Gyre, linking the northern part of the Antarctic Circumpolar Current with the Pacific South Equatorial Current. Although the primary productivity per unit area is modest compared to that of the other EBUEs, the Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since 1960s) of 8 million tons.yr^{-1} (http://www.seaaroundus.org/lme/13/1.aspx) although decadal-scale variations range from 2.5 to 13 million tons.yr^{-1}. While the anchoveta currently contributes 80% of the total catch, they alternate with sardines on a multi-decadal scale, with their dynamics mediated by the approach and retreat of subtropical waters to and from the coast [*Alheit and Bakun*, 2010] in a cycle that does not appear to be due to anthropogenic climate change. Thus, from the late 1970s to early 1990s, sardines were more important [*Chavez et al.*, 2003]. The other major commercial fish species are jack mackerel among the pelagic fish, and hake among the demersal fish.

The Humboldt Current has not shown a warming trend in SST over the last 60 years (Table 30-2) which is consistent other data sets (1982-2006, HadISST1.1, [*Belkin*, 2009]; 1985-2007, Pathfinder [*Demarcq*, 2009]. Wind speed has increased in the central portions of the Humboldt Current although wind has decreased in its southern and northern sections (Figure 30-6A, [*Demarcq*, 2009]. The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity, which may be exerting opposing drivers on upwelling which (if they intensify) would decrease temperatures.

Primary production is suppressed during warm El-Niño events and amplified during cooler La-Niña phases. These changes affect primary production that propagates through to higher trophic levels [*Chavez et al.*, 2003; *Tam et al.*, 2008; *Taylor et al.*, 2008]. However, in addition to the trophic impacts, there is also a significant thermal impact directly on organisms, which varies depending on thermal adaptation window for each species. A 37-year zooplankton time series for the coast of Peru showed no persistent trend in abundance and diversity [*Ayón et al.*, 2004], although observed shifts coincided with the shifts in the regional SST. As for the other EBUEs, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least one study [*Gutierrez et al.*, 2011] provides additional evidence that the northern Humboldt Current has cooled (due to upwelling intensification) since the 1950s, a trend matched by increasing primary production. This is not entirely consistent with the lack of significant change over the period from 1950-2009 (Table 30-2). Nevertheless, these relationships are likely to be complex in their origin, especially in their sensitivity to the long-term changes associated with ENSO and PDO.

30.5.5.2. Key Risks and Vulnerabilities

There is *robust evidence* and *high agreement* that EBUEs are vulnerable to changes that influence the intensity of currents, upwelling and mixing (i.e. SST, wind strength and direction), oxygen content, ocean chemistry, and the supply of organic carbon to deep offshore locations. Extent to which particular EBUEs are vulnerable to these factors depends on their location [*Gruber*, 2011] Figure 3) and other factors such as other sources of nutrient input and fishing pressure [*Bakun et al.*, 2010]. This complex interplay between regional and global drivers means that our understanding of how factors such as upwelling within the EBUEs are likely to respond to further climate change is uncertain (Box 30-1).

In the GCM ensembles examined (Table 30-3), modest rates of warming (0.22 – 0.91°C) occur within the four EBUEs, with the differences between the four RCP models examined being minimal in the near term (2010-2039) and range from 0.22ºC to 0.93ºC. By the end of the century, however, EBUE temperatures range from 0.07ºC to 1.02ºC warmer than today under RCP 2.6, and 2.52ºC to 3.51ºC under RCP8.5 (Table 30-4). These high temperatures have the potential to increase stratification of the water column and substantially reduce overall mixing in some areas and sometimes. Contrary to this, is the potential strengthening of coastal wind systems which would intensify upwelling and stimulate primary productivity through the increased injection of nutrients into the photic zone within the EBUEs (Box 30-1). *Garreaud and Falvey* [2009] explored how wind stress along the South

American coast would change by 2100 under B2 and A2 IPCC scenarios. Using an ensemble of 15 coupled atmosphere–ocean Global Circulation Models (GCMs), upwelling favorable southerly wind systems along the subtropical coast of South America increased, extending and strengthening conditions required for upwelling.

Changes in the intensity of upwelling within the EBUEs are *very likley* to drive fundamental changes to the abundance, distribution and viability of their resident biota although their nature and direction is *uncertain*. In some cases, large-scale decreases in primary productivity and dependent fisheries are projected to occur for EBUEs [*Blanchard et al.*, 2012] while other projections question the strong connection between primary productivity and fisheries production [*Arístegui et al.*, 2009]. Increased upwelling intensity also has potential disadvantages. Elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed (Figure 30-16), where it is *virtually certain* to increase microbial respiration and hence increase oxygen stress [*Bakun et al.*, 2010; *Weeks et al.*, 2002]. Increased wind stress may also increase turbulence, breaking up food concentrations (affecting trophic transfer), or causing excessive offshore advection, which could remove plankton from shelf habitats.

The central issue for the EBUEs is therefore whether or not upwelling will intensify, and if so, whether the detrimental impacts of upwelling intensification on O_2 and CO_2 will outweigh its benefits to primary production and associated fisheries. These changes need to be considered together with the many other changes that are *likely*. As projected atmospheric CO_2 concentrations increase, upwelling waters will become increasingly corrosive (*very high confidence*). Although there is substantial evidence from other systems that these changes are likely to impact the biota of EBUEs, there are many uncertainties.

30.5.6. Subtropical Gyres

Subtropical gyres (STG) dominate the Pacific, Atlantic and Indian Oceans and consist of large stable water masses that circulate clockwise (northern hemisphere) and anticlockwise (southern hemisphere) due to the Coriolis Effect (Figure 30-1, Figure 30-13A). The oligotrophic areas at the core of the STGs represent one of the largest habitats on Earth, contributing 21.2% of the ocean primary productivity and 8.3% of the global fish catch (Table 30-1). A number of small island nations are found within this region. While many of the observed changes within these nations have been described in previous chapters, region-wide issues and impacts are discussed here given the strong linkages between ocean and coastal issues (e.g. Chapters 5 and 29).

30.5.6.1. Observed Changes and Potential Impacts

The central portions of the STG are oligotrophic (Figure 30-13A). Temperatures within the STGs of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL) and South Atlantic (SATL) have increased at rates of 0.024, 0.0236, 0.0322, 0.0248, and 0.0266°C.yr^{-1} from 1998 to 2010 respectively [*Signorini and McClain*, 2012](Figure 30-13B). This is consistent with changes observed from 1955 to 2005 (0.21-0.53ºC, Table 30-2). Salinity has decreased across the North and South Pacific STGs (Figure 30-6D; WGI 3.3.3.1), consistent with warmer sea temperatures and an intensification of the hydrological cycle [*Boyer*, 2005].

It is *very likely* that the tropical gyres in the North and South Pacific have expanded since 1993 (*high confidence*), with these changes being *as likely as not* consequences of changes in wind forcing and long-term variability (WG1 3.6.3). Chlorophyll levels have decreased in NPAC, IOCE and NATL by 9%, 12% and 11%, respectively over and above the inherent seasonal and interannual variability from 1998 to 2010 [*Vantrepotte and Melin*, 2011] Figure 30-13 C). Chlorophyll levels did not change statistically in the remaining two gyres (SPAC and SATL; which has been confirmed for SPAC by [*Lee and McPhaden*, 2010; *Lee et al.*, 2010]). Further, over the period 1998-2007, median cell diameter of key species of phytoplankton exhibited statistically significant linear declines of about 2% in the North and South Pacific, and 4% in the North Atlantic Ocean [*Polovina and Woodworth*, 2012]. Changes in chlorophyll and primary productivity in these sub-regions have been noted before [*Gregg et al.*, 2005; *Polovina et al.*, 2008] and are influenced by seasonal and longer term sources of variability (e.g. ENSO, PDO, 6.3.1, Figure 6-10). These changes represent a significant expansion of the world's most unproductive waters, although caution must

be exercised given the limitations of satellite detection methods (6.2, 6.3) and the shortness of records relative to longer-term patterns of climate variability. There is *high confidence* that changes that reduce the vertical transport of nutrients into the euphotic zone (e.g. decreased wind speed, increasing surface temperatures and stratification) will reduce the rate of primary productivity and hence fisheries.

[INSERT FIGURE 30-13 HERE
Figure 30-13: A. Map of SeaWiFS chl-a climatology. The white polygons define the sub-regions that were analyzed and represent the major sub-regions considered as sub-tropical gyres by Signorini and McClain (2012). B. Time series of anomalies in chl-a and B. Sea Surface Temperature SST for STGs in North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE) North Atlantic (NATL) and South Atlantic (SATL) Oceans.]

30.5.6.1.1. Pacific Ocean STGs

Pacific climate is heavily influenced by the position of the Inter-tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation. These features are also strongly influenced by inter-annual to inter-decadal climate patterns of variability including the ENSO and PDO. The current understanding of how ENSO and PDO are likely to change as average global temperatures increase is *uncertain* [*Collins et al.*, 2010], WG1 12.4.4.2). The position of both ITCZ and SPCZ vary seasonally and with influences such as ENSO [*Lough et al.*, 2011], with a northward migration during the northern hemisphere summer and a southward migration during the southern hemisphere summer. These changes determine the timing and extent of the wet and dry seasons in SPAC and NPAC sub-regions, along with the West Pacific Monsoon [*Ganachaud et al.*, 2011]. Tropical cyclones are prominent in the Pacific (particularly the western Pacific), and CBS sub-regions between 10°-30° north and south of the equator, although the associated storm systems may occasionally reach higher latitudes. Spatial patterns of cyclones vary with ENSO, spreading out from the Coral Sea to the Marquesas Islands during El Niño and contracting back to the Coral Sea, New Caledonia and Vanuatu during La Niña [*Lough et al.*, 2011]. Historically, there has been almost twice as many land falling tropical cyclones during La Niña as opposed to El Niño years off the East coast of Australia, with a declining trend in the number of severe tropical cyclones from 0.45 per year in the early 1870s to 0.17 per year in recent times [*Callaghan and Power*, 2011].

The Pacific Ocean underwent an abrupt shift to warmer sea temperatures in the mid-1970s as a result of both natural (e.g. PDO) and climate forcing [*Meehl et al.*, 2009] (*high confidence*). This change coincided with a similarly sharp change in rainfall observed across the Pacific [*Griffiths et al.*, 2003], especially from 150-180°W. Countries such as the Cook Islands, Tonga, Samoa and American Samoa and Fiji tend to experience drought conditions as the SPCZ (with cooler sea temperatures) moves toward the north-east during El Niño (*moderate confidence*). The opposite is true during La Niña conditions. The impact of changing rainfall on the countries of the Pacific STGs discussed in greater detail elsewhere (5.3.2.5, 5.3.2.6, 29.3.2.2, Table 29-1). While these changes are due to different phases of long-term variability in the Pacific, they illustrate the ramifications and sensitivity of the Pacific to changes in climate change.

Elevated sea temperatures within the Pacific Ocean have increased the frequency of widespread mass coral bleaching and mortality since the early 1980s [*Baker et al.*, 2008; *Donner et al.*, 2010; *Hoegh-Guldberg*, 1999; *Hoegh-Guldberg and Salvat*, 1995; *Mumby et al.*, 2001]. There are few if any scientific records of mass coral bleaching and mortality prior to this period [*Hoegh-Guldberg*, 1999]. Rates of decline in coral cover on coastal coral reef ecosystems range between 0.5 and 2.0% per year depending on the location within the Indo Pacific region [*Bruno and Selig*, 2007; *De'ath et al.*, 2012; *Hughes et al.*, 2011; *Sweatman et al.*, 2011]. The reasons for this decline are complex and involve non-climate change related factors (e.g. coastal pollution, overfishing) as well is global warming and possibly acidification. A recent comprehensive analysis of the impacts of coral bleaching and mortality concluded "that bleaching episodes have resulted in catastrophic loss of coral reefs in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics" [*Baker et al.*, 2008]. Increasing sea levels have also caused changes in seagrass and mangrove systems. *Gilman et al.* [2007] found a reduction in mangrove area with sea level rise, with the observed mean landward recession of three mangrove areas over four decades being 25, 64, and 72 $mm.yr^{-1}$, 12-37

times faster than the observed rate of sea-level rise. Significant interactions exist between climate change and coastal development, where migration shoreward depends on the extent to which coastlines have been modified or barriers to successful migration have been established.

Reduced ocean productivity of the STGs [*Sarmiento et al*., 2004; *Signorini and McClain*, 2012] reduces the flow of energy to higher trophic levels, such as those of pelagic fish and sharks [*Le Borgne et al*., 2011]. The distribution and abundance of fisheries stock such as tuna is also sensitive to changes in sea temperature and hence long-term variability such as ENSO and PDO. The redistribution of tuna in the Western central equatorial region has been related to the position of the oceanic convergence zones, where the warm pool meets the cold tongue of the Pacific. These changes have been reliably reproduced by population models that use temperature as a driver of the distribution and abundance of tuna [*Lehodey et al*., 1997; *Lehodey et al*., 2006].

30.5.6.1.2. Indian Ocean STG

Like the Pacific Ocean, the Indian Ocean plays a crucial role in the global weather patterns with teleconnections throughout Africa, Australasia, Asia and the Americas (e.g. [*Clark et al*., 2000; *Manhique et al*., 2011; *Meehl and Arblaster*, 2011; *Nakamura et al*., 2011]. Increasing sea level, temperature, storm distribution and intensity, and changing ocean chemistry set to influence the broad range of physical, chemical and biological aspects of the Indian Ocean. Coral reef ecosystems in the Indian Ocean gyre system were heavily impacted by record positive sea temperature anomalies seen in the southern hemisphere February-April 1998 [*Ateweberhan et al*., 2011] *robust evidence, high agreement, high confidence*). Coral cover across the Indian Ocean region has declined from 37-39% coral cover in the period 1987 to 1997 to approximately 22% coral cover (1999-2000). Responses to the anomalously hot conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases coral cover from 40 to 53% (1977 to 1997) to 7% (1999-2000) after the 1998 event (*high confidence*, [*Ateweberhan et al*., 2011]). Coral reefs lining islands in southern India and Sri Lanka experienced similar decreases in coral cover (45% to 13%). Islands in the South West Indian ocean (Comoros, Madagascar, Mauritius, Mayotte, Reunion, and Rodrigues) experienced much lower impacts (44%, 1977-1997 to 40%, 1999-2000). Recovery from these impacts has been variable with sites such as those around the central Indian Ocean islands exhibiting fairly slow recovery (13% by 2001-2005) while those around southern India and Sri Lanka showing much higher rates (achieving a mean coral cover 37% by 2001-2005; [*Ateweberhan et al*., 2011]. These impacts on key reef-building species are likely to drive major changes in the abundance and composition of fish populations in coastal areas, and affect other ecosystem services that are important for underpinning tourism and coastal protection (Box CC-CR).

Pelagic fisheries that involve tuna and other pelagic species are very valuable to many small island states within the Indian Ocean (Chapter 29). As with Pacific pelagic fisheries, the distribution and abundance of pelagic fisheries in the Indian Ocean is greatly influenced by sea temperature. The anomalously high sea temperatures of 1997-98 (leading to deep mixed layer anomalies) coincided with anomalously low primary production in the Western Indian Ocean and a major shift in tuna stocks within the Indian Ocean [*Menard et al*., 2007; *Robinson et al*., 2010], *high confidence*). Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which is unprecedented for the tuna fishery. As a result of these changes, many countries throughout the Indian Ocean lost significant tuna related revenue. In the case of the Seychelles in 1998, direct, indirect and induced economic effects of the tuna industry expenditure declined by 58, 26 and 35%, respectively [*Robinson et al*., 2010]. Observations over the period 1991 to 2007 reveal interactions between depth of the mixed layer and depressed chlorophyll concentrations. In 2007, tuna fishing revenue was again reduced by strong surface warming, the deepening of the mixed layer, and associated with modest reduction in primary productivity. These trends highlight the overall vulnerability of tuna fishing countries to climate change, which is similar for many other countries in the other major oceans of the world.

30.5.6.1.3. Atlantic Ocean STGs

The SST have increased within the STGs of the Atlantic Ocean (Figure 30-13, [*Belkin*, 2009; *Signorini and McClain*, 2012]. The strength of surface winds has also declined over a large portion of the STGs in the Atlantic Ocean (Figure 30-6A, *high confidence*). These changes have influenced the distribution of key fishery species as well the ecology of coral reefs in Bermuda [*Baker et al*., 2008; *Wilkinson and Hodgson*, 1999] and in the eastern Caribbean [*Eakin et al*., 2010]. Small island nations such as Bermuda depend on coral reefs for fisheries and tourism and are vulnerable to further increases in sea temperature that cause mass coral bleaching and mortality (Box CC-CR; Figure 30-12). As with the other STGs, phytoplankton communities and pelagic fish stocks are sensitive to temperature changes that have occurred over the past several decades. Observations to the changes have enabled models to be developed which have a high degree of accuracy in projecting the distribution and abundance of these elements within the Atlantic region generally [*Cheung et al*., 2011].

30.5.6.2. Key Risks and Vulnerabilities

The vast STGs of the Atlantic, Pacific and Indian oceans are responsive to increasing temperature which is *very likely* to increase water column stratification which is *likely* to reduce surface concentrations of nutrients, and consequently, primary productivity (*medium confidence*). Warming is projected to continue (Table 30-4), with substantial increases in the risk and vulnerability associated with systems that have been observed to change so far (*high confidence*; Figure 30-12). Under RCP2.6, the temperatures of the STGs are likely to increase by 0.20-0.55°C warmer in the near term (2010-2039) and between 0.00-0.87°C by the end of the century (Table 30-4). Under RCP8.5, however, surface temperatures of the world's STGs are projected to be 0.49-0.90°C warmer in the near term (2010-2039) and 2.05-3.44°C warmer by the end of the century (Table 30-4). These changes in temperature are *very likely* to increase water column stability, reduce the depth of the mixed layer, and influence key parameters such as nutrient availability and oxygen concentrations. It is *uncertain* how longer term sources of variability such as ENSO and PDO will change and ultimately influence these trends.

The world's most oligotrophic ocean sub-regions will continue to expand over coming decades with consequences for ecosystem services such as gas exchange, fisheries and carbon sequestration if a large part of recent changes have an origin in climate change. *Polovina et al*. [2011] explored this question for the North Pacific using a climate model that included a coupled ocean biogeochemical component to investigate potential changes under an SRES A2 scenario (~RCP 6.0 – 8.5). Model projections demonstrated that the STG expanded by approximately 30% by 2100, driven by the northward drift of the mid-latitude westerlies and enhanced stratification of the water column. The expansion of the STG occurred at the expense of the equatorial upwelling and other regions within the North Pacific. The total primary production and fish catch of the new enlarged STG is projected to increase by 26% although primary production per area declined slightly [*Polovina et al*., 2011].

Understanding how storm frequency and intensity is likely to change represents a significant question for many countries within the STGs. Projections of increasing sea temperature are *likely* to change the behavior of tropical cyclones. At the same time, the maximum wind speed and rainfall associated with cyclones is *likely* to increase, although future trends in cyclones and severe storms are *very likely* to vary from region to region (WG1 Box 14.2). Patterns such as "temporal clustering" can have a strong influence on the impact of tropical cyclones on ecosystems such as coral reefs [*Mumby et al*., 2011], although how these patterns are likely to change within the STG is uncertain at this point. There is, however, *medium to high confidence* that an intensifying hydrological cycle is likely to increase precipitation in many areas (WG1 2.6.3, 14.2.5), although longer droughts are also expected in other STGs (*medium confidence*). Improving our understanding of how weather systems associated with features such as the South Pacific Convergence Zone (14.3.1.2) are likely to vary is critical to climate change adaptation of a large number of nations associated with the STGs. Developing an understanding of how water temperature, climate systems such as SPCZ and ITCZ, climate change, and long-term cycles such as ENSO interact will be essential in this regard.

The impacts of projected sea temperatures on the frequency of coral bleaching and mortality within two key sub-regions within the STG are outlined in Box CC-CR and Figure 30-12. As with other sub-regions dominated by coral

reefs, mass coral bleaching and mortality becomes an annual risk under all scenarios, with mass mortality events beginning to occur every 1-2 years by 2100 (Box CC-CR, Figure 30-12). Coral dominated reef ecosystems (areas with more than 30% coral cover) are *very likely* disappear under these circumstances by the mid to late part of this century [*Bell et al.*, 2013a; *Donner et al.*, 2005; *Dove et al.*, 2013; *Frieler et al.*, 2012]. The loss of substantial coral communities has implications for the three-dimensional structure of coral reefs (Figure 30-12; Box CC-CR), and the role of the latter as habitat for organisms such as fish [*Bell et al.*, 2013a; *Hoegh-Guldberg*, 2011; *Hoegh-Guldberg et al.*, 2011b; *Pratchett et al.*, 2011a]. The impacts of increasing sea temperature can be exacerbated by increasing ocean acidification with potential impacts on calcification [*Doney et al.*, 2009; *Hoegh-Guldberg et al.*, 2007; *Kleypas et al.*, 1999] *medium confidence*), reef metabolism and community calcification [*Dove et al.*, 2013], and other key ecological processes [*Munday et al.*, 2009; *Portner et al.*, 2007; *Portner et al.*, 2001], 6.2.2.4.4). Ocean pH within the STGs will continue to decrease as atmospheric carbon dioxide increases, bringing pH within the STGs to 7.7 (800 ppm) and 7.9 (450 ppm, Figure 30-7A; Box CC-OA). Aragonite saturation states will decrease to around 1.6 (800 ppm,) and 3.3 (450 ppm, Figure 30-7B). Decreasing carbonate ion situations and saturation states pose serious risks to other marine calcifiers such as encrusting coralline algae, coccolithophores, and a range of invertebrates [*Doney et al.*, 2009; *Feely et al.*, 2009]. Increasing sea temperatures and sea level are also likely to influence other coastal ecosystems (e.g. mangroves, seagrass meadows) in the Pacific although significant gaps and uncertainties exist (6.4.1.2.2, 29.3.1.4, [*Waycott et al.*, 2007]. There is *medium confidence* that many of the negative consequences for coral reefs, mangroves and seagrass meadows are *likely* to have negative consequences for dependent coastal fisheries (through destruction of habitat) and tourism industries [*Bell et al.*, 2011; *Pratchett et al.*, 2011a; *Pratchett et al.*, 2011b]Table 29.3, WGII Ch29, *medium confidence*).

Changes to sea temperature also lead to changes in the distribution of key pelagic fisheries such as Skipjack Tuna (*Katsuwonus pelamis*), Yellowfin Tuna (*Thunnus albacares*), Big-eye Tuna (*T. obesus*) and South Pacific Albacore Tuna (*T. alalunga*), which make up the majority of key fisheries in the Pacific Ocean. Changes in the distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate a close association of pelagic fish stocks and water temperature. As a result, populations of key pelagic fishery species are projected to move many hundreds of km east from where they are today [*Lehodey et al.*, 2008; *Lehodey et al.*, 2010; *Lehodey et al.*, 2011], *high confidence*) with implications for income, industry and food security across multiple Pacific Island nations [*Bell et al.*, 2011; *Cheung et al.*, 2010; *McIlgorm et al.*, 2010], 7.4.2.1, Table 29.2:, Table 29.3, *high confidence*). Our understanding of the impacts of reduced oxygen on pelagic fish populations is uncertain although there is a *high agreement* on the potential physiological impacts (6.3.3). Those species that are intolerant to hypoxia, such as tuna, will have their depth range compressed, which may reduce their vulnerability to being caught (positively) and overall fisheries habitat and productivity (negatively, [*Stramma et al.*, 2010; *Stramma et al.*, 2011]; *high confidence*). Despite the importance of these potential changes, our understanding of the full range of impacts is limited at this point.

The shift in habitat for top predators in the Pacific was examined by *Hazen et al.* [2012] who used tracking data from 23 marine species and associated environmental variables to predict increases and decreases of up to 35% in core habitat for many species within the Pacific. Potential habitat contracted for Blue Whales, Salmon Sharks, Loggerhead Turtles, Blue Shark and Make Sharks, while potential habitat expanded for Sooty Shearwaters, Black Footed Albatross, Leatherback Turtles, White Sharks, Elephant Seals, Albacore, Bluefin and Yellowfin Tuna [*Hazen et al.*, 2012]. These directional changes represents an opportunity to participate and apply anticipate change and to apply large-scale management strategies to preserve these valuable species.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the deep sea are challenging due to difficulty of access and scarcity of long-term, comprehensive observations [*Smith et al.*, 2009]. The size of this habitat is also vast, covering well over 60% of the earth's surface and stretching from top of the mid-oceanic ridges to bottom of deep ocean trenches. The fossil record in marine sediments reveals that the deep ocean environment has undergone large changes due to climate change in the past [*Knoll and Fischer*, 2011]. The paleo-skeletal record shows it is the rate, not simply magnitude, of climate change (temperature, oxygen and carbon dioxide) that is critical to marine life. The rate of change today in key parameters *very likely* exceeds that of other major events in Earth history. Two primary

time scales are of interest. The first is the slow rate (century scale) of ocean circulation and mixing and consequently the slow rate at which deep-sea ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at surface of the ocean, which represents a critical food supply to deep-sea animals [*Smith et al*., 2009; *Smith et al*., 2008]. Since the upper ocean is currently experiencing warming, increased stratification, and changing productivity (WG1 3.2.2) there is evidence (*medium confidence*) of impacts on quite different time scales between the slow warming at depth and the more rapidly changing (decreasing/increasing) food supply to deep-sea animals that falls from above.

30.5.7.1. Observed Changes and Potential Impacts

The greatest rate of change of temperature is occurring in the upper 700 m of the ocean (WG 1 3.2, *very high confidence*), although smaller yet significant changes are occurring at depth. The deep-sea environment is typically cold (~ 1-4°C) although abyssal temperatures in SES can be higher (e.g. Mediterranean ~12°C, Red Sea ~22°C). In the latter case, deep-sea populations can thrive in these environments as well, illustrating the variety of temperature conditions that differing species of abyssal life have adapted to. Individual species, however, are typically constrained within a narrow thermal and oxygen-demand window of tolerance [*Portner*, 2010] and therefore it is *very likely* that major shifts in the distribution of deep-sea species will occur. Warming over multiple decades has been observed below 700 m [*Levitus et al*., 2005; *Levitus et al*., 2009], with warming being minimal at mid-range depths (2000-3000 m), and increasing towards the sea floor in some sub-regions (e.g. Southern Ocean) (WGI Ch3). For the deep Atlantic Ocean, the mean age of deep-waters (mean time since last exposure to the atmosphere) is ~250 years; the oldest deep waters of the Pacific Ocean are >1,000 years old. The patterns of ocean circulation are clearly revealed by the penetration of tracers and the fossil-fuel CO_2 signal itself into the abyss [*Sabine et al*., 2004]; the time scale for full equilibration of deep ocean waters and their ecosystems with modern warming and CO_2 levels is many centuries [*Wunsch and Heimbach*, 2008].

Temperature accounts for ~86% of the variance in the export of organic matter to the deep sea (*moderate confidence*)[*Laws et al*., 2000]. Consequently, upper-ocean warming will (*medium confidence*) reduce the export of organic matter to the deep sea, impacting the distribution and abundance of deep sea organisms and associated food webs and ecosystem processes [*Smith Jr and Kaufmann*, 1999; *Smith et al*., 2008]. Most organic matter entering the deep ocean is recycled by microbial systems at relatively shallow depths [*Buesseler et al*., 2007], at rates which are temperature dependent. Upper ocean warming will increase the rate of sub-surface decomposition of organic matter (*high confidence)*, thus intensifying the intermediate depth oxygen-minimum zones [*Stramma et al*., 2008; *Stramma et al*., 2010] and reducing food supply to the abyssal ocean.

Quantifying these effects is difficult since complex ecosystem responses are likely and information is sparse. Food supply to depths below the euphotic zone is about 20% of net primary productivity. The vast majority of this is recycled by microbes at depths shallower than 1,000. The net result is that with warming of the upper ocean food supply to the deep sea will decrease. If the temperature dependence assumed by models such as that of *Laws et al*. [2000] is correct, then warming of the ocean basins by 2.5ºC (Table 30-4) would reduce the fraction exported to the deep sea by about 5%. Warming of intermediate waters will increase respiration at mid-water depths. The temperature dependence of mid-water respiration rates is not well known, but is *likely* (*moderate confidence*) to be similar to microbial rates in environments such as soils and sediments with a Q_{10} of about 2.5 [*Thamdrup et al*., 1998]. This suggests that a reduction in food supply to the deep sea from 20% to 16% of global net primary production (7.2 Gt C yr-1) could occur (medium confidence) under a 2.5ºC warming of the upper ocean. The impacts of climate change on other deep sea communities such as hydrothermal vent ecosystems are unknown [*Van Dover*, 2012].

The oxygen concentrations of the deep areas of the Ocean are decreasing [*Helm et al*., 2011b; *Karstensen et al*., 2008; *Keeling et al*., 2010; *Stramma et al*., 2008]. The largest signals occur at intermediate water depths shallower than 1,000 m [*Nakanowatari et al*., 2007; *Whitney et al*., 2007], but some waters >1,000 m depth are also experiencing decline [*Falkowski et al*., 2011; *Jenkins*, 2008]. The quantity of dissolved oxygen will be reduced with ocean warming due to direct effects on solubility (*high confidence*) with these effects being widely distributed [Shaffer et al. 2009]. It is also *virtually certain* that metabolic rates of all animals and microbial respiration rates will

increase with temperature [*Brown et al.*, 2004]. Thus, increased microbial activity and reduced oxygen solubility at higher temperatures will have additive impacts on the decline of oxygen (*high confidence*). Deep-sea waters have relatively high pO_2 due to the thermodynamic effects of pressure, and also from low microbial consumption rates associated with the small supply of organic matter. Oxygen concentrations will be less well oxygenated at mid depths as compared to deepest sites within the ocean which experience the highest pO_2 on Earth due to the very high pressures *(very high confidence)*.

Increasing deep water under-saturation for calcite and aragonite will impact carbonate shell formation and dissolution as has happened many times in Earth's past ([*Zeebe and Ridgwell*, 2011](*high confidence)*. Some cold-water deep-sea corals (reported down to 3,500m) already exist in waters under-saturated with respect to aragonite [*Lundsten et al.*, 2009]. These corals will face reduced calcification and growth rates from decreased food supply and altered seawater carbonate concentrations and pH (*high confidence*) [*Guinotte et al.*, 2006].

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to deep-water communities through increasing temperature, and decreasing oxygen, carbonate chemistry, and pH (*high confidence*). The resulting changes to the flow of organic carbon to some parts of the deep ocean (e.g. STGs) are very likely to impact deep-ocean ecosystems (*medium confidence*). Changes in temperature and the supply of organic carbon from surface waters are likely to interact and increase the risk of impacts to deep-ocean ecosystems. Changes in temperature, oxygen, and CO_2 may also increase the vulnerability of the daily vertical migration of mid-water populations. As with the deep sea generally, there is a need to fill in the substantial gaps that exist in our knowledge and understanding of the world's largest habitat and its responses to rapid anthropogenic climate change.

30.5.8. Detection and Attribution of Climate Change Impacts with Confidence Levels

The preceding analysis has identified a wide range of physical, chemical and ecological components that have changes over the decades and the last century. In some cases, confidence in both the detection and attribution of the changes to climate change is high. In other cases, confidence varies in both elements leading to lower levels of certainty surrounding whether or not specific changes can be attributed to anthropogenic climate change. Figure 30-14 summarises a number of examples from the Ocean as a region together with the degree of confidence in the detection and attribution steps. Physical and chemical changes such as ocean warming and acidification, confidence is extremely high that changes are being detected and they are due to climate change. Several ecological responses also fall in the upper corner such as changes in the distribution of marine plants and animals, and with respect to climate change driving more intense and frequent mass coral bleaching and mortality events. Other areas are of lower confidence, either because the detection of changes has been difficult (e.g. field evidence of declining calcification) yet models are in strong agreement that there should be a relationship, or where confidence is high when it comes to detection yet our models are in conflict (e.g. wind-driven upwelling). This analysis is further explored in Ch18.

[INSERT FIGURE 30-14 HERE
Figure 30-14: Expert assessment of degree of confidence in detection and attribution across sub-regions and processes (based on evidence explored throughout Chapter 30).]

30.6. Sectoral Impacts, Adaptation, and Mitigation Responses

The Ocean supports numerous sectors, many of which have been discussed in previous regional chapters of this assessment. Discussion here is restricted to economic, environmental and social sectors that have a direct relevance to the Ocean such as fisheries, tourism, shipping, oil and gas, maritime security, and renewable energy, as well as sectors that have significant non-market values such as ecosystem goods and services. The impacts of climate change on ocean sectors will be mediated through simultaneous changes in multiple environmental and ecological

variables (Figure 30-15). Many climate change impacts can be avoided, reduced or delayed by mitigation, yet both short-term and longer-term adaptation are necessary to address impacts that result from warming, even under the lowest stabilization scenarios assessed.

[INSERT FIGURE 30-15 HERE
Figure 30-15: A. Summary of regional impacts and opportunities associated with climate change on the world's ocean region. B. Example of changes occurring within fisheries across the Ocean.]

Sectoral approaches dominate resource management in the Ocean (i.e. shipping tends to be treated in isolation from fishing within an area), yet cumulative and interactive effects of individual stressors are known to be ubiquitous and substantial [*Crain et al.*, 2008]. Climate change consistently emerges as a dominant stressor in regional to global-scale assessments [*Halpern and Floeter*, 2008; *Halpern et al.*, 2010; *Halpern et al.*, 2009a; *Halpern et al.*, 2009b; *Halpern et al.*, 2009c; *Selkoe et al.*, 2009], but land-based pollution, commercial fishing, invasive species, and commercial activities such as shipping all rank high in many places around the world, especially coastal waters [*Halpern et al.*, 2010; *Halpern et al.*, 2009a]. Such cumulative effects pose challenges to managing for the full suite of stressors to marine systems, but also present opportunities where mitigating a few key stressors can potentially dramatically improve overall ecosystem condition (e.g.[*Halpern et al.*, 2010]). The latter has often been seen as a potential strategy for reducing climate impacts on marine ecosystems by increasing ecosystem resilience, thus buying time while the core issue of reducing greenhouse gas emissions is tackled [*Hughes et al.*, 2003].

30.6.1. Natural Ecosystem Services

Human welfare is highly dependent on ecosystem services provided by the Ocean. Many of these services are provided from coastal and shelf areas, and are consequently addressed in other chapters. Oceans contribute provisioning (e.g. food, raw materials; see 30.6.3.1), regulating (e.g. gas exchange, nutrient recycling, carbon storage, climate regulation, water flux), supporting (e.g. habitat, genetic diversity) and cultural (e.g. recreational, spiritual) services [Millennium Ecosystem Assessment, 2005]. The accumulating evidence fundamental ecosystem services within the ocean are shifting rapidly should be of major concern, especially with respect to the ability of regulating and supporting ecosystem services to underpin current and future human population demands [Rockstrom et al., 2009].

Supporting, regulating and cultural ecosystem services tend to transcend the immediate demands placed on provisioning services, and are difficult to value in formal economic terms due to their complexity, problems such as double counting and the value of non-market goods and services arising from marine ecosystems generally [*Beaudoin and Pendleton*, 2012; *Fu et al.*, 2011]. Pursuing a formal valuation of ecological services from the Ocean, however, has the potential to provide adaptation options for stimulating more effective governance, regulation and ocean policy while at the same time potentially improving the management of these often vulnerable services through the development of market mechanisms and incentives [*Beaudoin and Pendleton*, 2012]. Other strategies have involved placing larger areas of the ocean under management in order to protect and maintain the health and function of ocean ecosystems [*Agardy et al.*, 2011; *Edgar*, 2011; *Game et al.*, 2009]. The planetary scale changes that are currently occurring, however, require concerted international action on the fundamental drivers of change (anthropogenic greenhouse gas emissions) otherwise many of the proposed adaptation options will fail.

Adaptation strategies that reduce the impact of climate change on ocean ecosystems and their services include managing local factors not related to climate change. Overfishing, pollution, deteriorating water quality, and habitat loss often interact with climate change to produce greater effects than if each were to occur on their own (i.e. producing synergistic interactions). Coral reefs, for example, will recover three times faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained [*Hughes et al.*, 2003], indicating that controlling overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of greenhouse gases and stabilises global temperature. In a similar way, 'Blue carbon' provides opportunities for mitigation and by extension to other ecosystems services, adaptation. Blue carbon is defined as the organic carbon trapped and stored within marine ecosystems such as phytoplankton, mangrove, seagrass and salt marsh ecosystems. Destroying and removing these ecosystems exposes organic carbon to the

atmosphere, leading to the oxidation and release into the atmosphere. Combining data on global area, land-use conversion rates and near surface carbon stocks for marshes, mangroves and seagrass meadows, *Pendleton et al.* [2012] revealed that the destruction of these three ecosystems was equivalent to 3-19% of the emissions generated by deforestation globally with economic damages estimated to be US$6-42 billion annually. In driving the preservation of coastal ecosystems, strategies involving Blue Carbon and other strategies can also enhance adaptation against sea level rise and storm damage, as well as maintaining habitat for fisheries species. The current understanding of Blue Carbon is uncertain given limited knowledge, methodologies and policies for measuring and implementing blue carbon strategies.

30.6.2. Economic Sectors

30.6.2.1. Fisheries

Capture fisheries and aquaculture supplied the world with 148 million tonnes of fish and shellfish in 2010. This production was valued at US$217.5 billion, and supplied 18.8 kg of protein-rich food per person in 2011 [*FAO*, 2012]. The world's oceans provided 64% of the total world fisheries in 2011. Production from marine aquaculture increased from 16 million tonnes in 2006 to 18 million tonnes in 2010 whereas marine capture fisheries declined over the same period from 80 to 77 million tonnes per year [*FAO*, 2012]. The significance of marine capture fisheries is also illustrated powerfully by the number of people engaged in small-scale marine fisheries in developing countries. These small-scale fisheries account for 28 million of the ~80 million tonnes of fish caught from the ocean, and provide jobs for more than 47 million people – about 12.5 million fishers and another 34.5 million people engaged in post-harvest activities [*Mills et al.*, 2011].

The stagnation of marine capture fisheries production is attributed to full exploitation of 60% of the world's fisheries, and overexploitation of another 30% of fisheries [FAO, 2012]. The main problems with industrial fisheries include illegal, unreported and unregulated fishing; ineffective implementation of monitoring, control and surveillance and overcapacity in fishing fleets [*World Bank/FAO,* 2008; *FAO*, 2012].]. Such problems are being progressively addressed in several developed and developing countries [*Hilborn;* 2007; *Worm et al.,* 2009][*Pitcher et al.*, 2009], where investments have been made in stock assessment, strong management and application of the FAO Code of Conduct for Responsible Fisheries and the FAO Ecosystem Approach to Fisheries Management.

A different governance approach is needed in most cases for small-scale fisheries, which are often characterised by large numbers of politically weak fishers operating from decentralized localities, poor governance and insufficient data to monitor catches effectively [*Kurien and Willmann*, 2009; *Cochrane et al.* 2011; *Pomeroy and Andrew*, 2011]. For these fisheries, management that aims to avoid further depletion of overfished stocks is likely to be more appropriate in the short term than management aimed at maximising sustainable production. These aims can be achieved through (1) 'primary fisheries management', which uses simple harvest controls (e.g. size limits, closed seasons and areas, gear restrictions and protection of spawning aggregations) to avoid irreversible damage to stocks in the face of uncertainty [*Cochrane et al.* 2011], and (2) investing in the social capital and institutions needed for communities and governments to manage small-scale marine fisheries [*Hall et al.*, 2013; *Pomeroy and Andrew*, 2011].

Changes to sea temperature and other factors as a result of anthropogenic climate change is generating new challenges for fisheries as coastal and oceanic environments experience the loss of habitat, the spread of disease and invading species, and changes in the availability of food. There is *medium evidence* and *robust agreement* that these changes will change both the nature of fisheries and their ability to provide food and protein for hundreds of millions of people. These risks for ecosystems and fisheries vary from region to region (Figure 30-15, Chapter 7), with potential increases in fisheries production over the short term at high latitudes, and potential decreases at lower latitudes.

The challenges of optimising the economic and social benefits of both industrial and small-scale marine fisheries, which already include strategies to adapt to climatic variability [*Salinger et al.*, 2013], are now made more complex by climate change [*Cochrane et al.*, 2009; *Brander*, 2010; 2013]. Nevertheless, vulnerability assessments have

identified practical adaptations to assist enterprises, communities and households to reduce the risks from climate change and capitalise on the opportunities. The diversity of these adaptation options, and the policies needed to support them, are illustrated by the following examples.

30.6.2.1.1. Tropical fisheries based on top predators

Fisheries for Skipjack, Yellowfin, Big-eye and Albacore Tuna provide substantial economic and social benefits to the people of Small Island Developing States (SIDS). For example, tuna fishing license fees contribute substantially (up to 40%) to the government revenue of several Pacific Island nations [*Gillett*, 2009; *Bell et al.,* 2013b]. Tuna fishing and processing operations also contribute up to 25% of gross domestic product in some of these nations and employ over 12,000 people [*Gillett*, 2009; *Bell et al*., 2013b]. Considerable economic benefits are also derived from fisheries for top pelagic predators in the Indian and Atlantic oceans [*Bell et al*., 2013b; *FAO*, 2012]. Increasing sea temperatures and changing patterns of upwelling are projected to cause shifts in the distribution and abundance of pelagic top predator fish stocks (30.5.4, 30.5.5), with potential to create 'winners' and 'losers' among island economies as catches of the trans-boundary tuna stocks change within their exclusive economic zones [*Bell et al*., 2013b].

A number of practical adaptation options and supporting policies to minimize the risks and maximize the opportunities associated with the projected changes in distribution of the abundant Skipjack Tuna in the tropical Pacific have been identified [*Bell et al*., 2011; *Bell et al*., 2013a](Table 30-5). These adaptation and policy options include: (1) full implementation of the regional 'vessel day scheme' designed to distribute the economic benefits from the resource in the face of climatic variability, and other schemes to control fishing effort in subtropical areas; (2) strategies for diversifying the supply of fish for canneries in the west of the region as tuna move progressively east; (3) continued effective fisheries management of all tuna species; (4) energy efficiency programs to assist domestic fleets to cope with increasing fuel costs and the possible need to fish further from port; (5) the eventual restructuring of regional fisheries management organizations to help coordinate management measures across the entire tropical Pacific; and (6) provision of operational-level catch and effort data from all industrial fishing operations to improve models for projecting redistribution of tuna stocks during climate change [*Salinger et al.* 2013].

[INSERT TABLE 30-5 HERE
Table 30-5: Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from fisheries and aquaculture, and to maximize the opportunities. These measures are classified as 'win-win' (W-W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or 'lose-win' (L-W) adaptations, where benefits exceed costs in the short term but accrue under longer-term climate change (Modified from *Bell et al.* 2013a).]

Other adaptation options and policies have been recommended to increase access to tuna caught by industrial fleets for people in rapidly-growing urban centers. These options center on amending licensing conditions to ensure that sufficient high-quality tuna and by-catch are landed locally to provide the large quantities of fish needed for food security in Pacific Island nations [*Bell et al*., 2011; *Bell et al.,* 2013a]. Similar adaptation options and policy responses are expected to be relevant to the challenges faced by tuna fisheries in the tropical and subtropical Indian and Atlantic oceans.

30.6.2.1.2. Coral reef fisheries

Coral reefs provide habitats for a wide range of harvested fish and invertebrate species. Despite their importance to many developing countries, these ecosystems are under serious pressure from human activities that include deteriorating coastal water quality, sedimentation, ocean warming and acidification (30.3, 30.5, 7.2.13, Box CC-CR). These pressures are translating into a steady decline in live coral cover which is very likely to continue over the coming decades, even where integrated coastal zone management is practiced well. For example, coral losses around

Pacific Islands are projected to be as high as 75% by 2050 [*Bell et al.*, 2013a]. Even under the most optimistic projections (a 50% loss of coral by 2050), changes to state of coral reefs (Box CC-CR; Figure 30-12) are *very likely* to reduce the availability of associated fish and invertebrates that support many of the coastal fisheries in the tropics (*high confidence*). In the Pacific, the productivity of coral reef fisheries has been projected to decrease by at least 20% by 2050, which is also likely to occur in other coral reef areas globally given the similar and growing amounts of stress in these other regions (Table 30-2, 30.4). Other economic activities based on coral reef species, e.g. pearl farming, may also be impacted by changing sea temperature and ocean chemistry. Survival and growth of wild spat used to supply the pearl oysters for farms in Polynesia could decline as shells are weakened by lower aragonite concentrations [*Bell et al.*, 2011]. Reduced availability of aragonite may also affect pearl quality [*Welladsen et al.*, 2010].

Adaptation options and policies for building the resilience of coral reef fisheries to climate change suggested for the tropical Pacific include: (1) strengthening the management of catchment vegetation to improve water quality along coastlines: (2) reducing direct damage to coral reefs; (3) maintaining connectivity of coral reefs with mangrove and seagrass habitats; (4) sustaining and diversifying the catch of coral reef fish to maintain their replenishment potential; and (5) transferring fishing effort from coral reefs to near-shore Skipjack and Yellowfin Tuna resources by installing anchored fish aggregating devices close to shore [*Bell et al.*, 2011, 2013a] (Table 30-5). These adaptation options and policies represent a 'no regrets' strategy in that they provide benefits for coral reef fisheries and fishers irrespective of the impacts of climate change.

30.6.2.1.3. Northern Hemisphere HLSBS fisheries

The high latitude fisheries in the northern hemisphere span from around 30/35 ºN to 60ºN in the North Pacific and 80 ºN in the North Atlantic covering a wide range of thermal habitats from subtropical/temperate species to boreal/arctic species. The characteristics of these HLSBS environments as well as warming trends are outlined in 30.5.1 and Table 30-4. As a result of 30-years increase in temperature (Table 30-2; [*Belkin*, 2009; *Sherman et al.*, 2009], there has been a boost in fish stocks in high latitude fisheries in the northern hemisphere, particularly in the Norwegian spring-spawning herring which recovered from nearly extinction caused by a combination overfishing and cooler climate during the 1960s [*Toresen and Østvedt*, 2000]. The major part of high-latitude fish stocks, pelagic as well as demersal, are boreal species located north of 50ºN. Climate change is projected to increase high latitude plankton production and displace zooplankton and fish species poleward. As a combined result of these changes future, the abundance of fish (particularly boreal species) may increase in the northernmost part of the high latitude region [*Cheung et al.*, 2011] although moderately in some regions.

Both demersal and pelagic fish have shown considerable variation in abundance and distribution with climate fluctuation and climate change, but the changes in distribution and migration of the pelagic fishes are considerably larger. These changes have increased tensions leading to what many consider the first climate change related conflicts between fishing nations (30.6.5), which has emphasized the importance of developing international collaboration and frameworks for decision making (30.6.7, 15.4.3.3). The Atlantic mackerel has been a shared stock between EU and Norway due to its newer historical distribution. The recent advancement of the Atlantic mackerel into the Icelandic EEZ during summer has resulted in fishing from Iceland outside internationally agreed fishing quotas. Earlier records of mackerel during first half of 20th and second half of 19th century show, however, that mackerel has been present in Icelandic waters also in the earlier warming periods [*Astthorsson et al.*, 2012]. In the Barents Sea, the Northeast Arctic cod reached record-high abundance during 2012 and also reached its northernmost distribution, 82 ºN, ever recorded. A further northward migration is impossible since this would be into the deep-sea Polar Basin beyond the habitat of shelf species. A further advancement eastwards on the Siberian shelf is, however, possible. The Northeast Arctic cod is shared exclusively by Norway and Russia. Up to now there has been a good agreement between those two nations on the management of the stock.

The HLSB fisheries make up a large-scale high-tech industry with large investments in highly mobile fishing vessels, equipment and land-based industries. Knowledge on how climate fluctuations and change impacts growth, recruitment and distributions in fish stocks is presently not utilized in management strategies for fisheries. These strategies are vital for fisheries that hope to cope with the challenges of a changing ocean environment, and are

centrally important for any attempt to develop ecosystem-based management and sustainable fisheries under climate change. The large pelagic stocks with their climate-dependent migration pattern are shared among several nations. Developing equitable sharing of fish quotas is a needed adaption for a sustainable fishery. Factors presently taken into account in determining the shares of quotas are the historical fishery, bilateral exchanges of quotas for various species, and occupation time of the stocks in the various EEZs. Some of the problems and options are discussed further in 30.6.7.

30.6.2.2. Tourism

Tourism recreation represents one of the world's largest industries, accounting for 9% (> US$6 trillion) of global GDP and employing over 255 million people. A large proportion of tourism occurs within coastal and marine settings. It is expected to grow by an average of 4% annually and reach 10% of global GDP within the next 10 years [*WTTC*, 2012]. As with all tourism, that which is associated with the ocean is heavily influenced by climate change, global economic and socio-political conditions, and their interactions [*Scott et al.*, 2012a]. Climate change by impacting ecosystems negatively (e.g. coral reefs) is reducing destination appeal, increasing operating costs and bringing increased uncertainty into a highly sensitive business environment [*Scott et al.*, 2012a].

Several facets of the influence of climate change on the Ocean directly impact tourism. Sea level rise through its influence on coastal erosion and submergence, salinization of water supplies, and changes to storm surge increase the vulnerability of coastal tourism infrastructure, tourist safety and iconic ecosystems (*high confidence*, 30.3.1.2, 5.3.2.4, [*IPCC*, 2012],Table SPM.1). Approximately 29% resorts in the Caribbean are within 1 m of the high tide mark, with 60% being at risk of beach erosion from rapid sea level rise [*Scott et al.*, 2012b]. Extreme events such as violent storms, long periods of drought, and/or extreme precipitation events can decrease the attractiveness and reputation of tourist destinations (5.3.2.4, [*IPCC*, 2012]).

Increasing sea temperatures (30.3.1.1) through their influence on the movement of organisms and the health of ecosystems such as coral reefs can change the attractiveness of locations and the opportunities for tourism (Box CC-CR, [*UNWTO and UNEP*, 2008]. Mass coral bleaching and mortality (triggered by elevated sea temperatures) also has the potential to decrease the appeal of diving related tourism, although the awareness by tourists (e.g. < 50% of tourists were concerned about coral bleaching during 1998) and expected economic impacts has been found to be uncertain [*Scott et al.*, 2012a]. Some studies, however, have picked up reduced tourists satisfaction and the identification of 'dead coral' being one of the reasons for disappointment at the end of the holiday [*Westmacott et al.*, 2001]. Other forms of nature-based tourism are also vulnerable to climate change. For example, the whale watching businesses ($1 billion worldwide in 2001) will be affected by climate change impacts on whale distributions, abundance, and species composition [*Lambert et al.*, 2010]. Anticipated changes include a decline of deep-water whale species diversity in the tropics and increases at higher latitudes [*Whitehead et al.*, 2008].

Tourists respond to changes in factors such as weather and opportunity by expressing different preferences. For example, preferred conditions and hence tourism are projected to shift towards higher latitudes with climate change, or from summer to cooler seasons [*Amelung et al.*, 2007]. Options for adaptation by the marine tourism sector include: (1) identifying and responding to inundation risks with current infrastructure, and planning for projected sea level rise when building new tourism infrastructure (5.6; Scott et al. 2012); (2) promote shoreline stability and natural barriers by preserving ecosystems such as mangroves, salt marsh and coral reefs (5.6, Scott 2012); (3) deploying forecasting and early warning systems in order to anticipate challenges to the structure, appeal, and visitors [*IPCC*, 2012; *Strong et al.*, 2011]; (4) preparation of risk management and disaster preparation plans in order to respond to extreme events; (5) reducing the impact of other stressors on ecosystems and build resilience in iconic tourism features such as coral reefs and mangroves, and (6) educating tourists to improve understanding the impacts of climate change over those stemming from local stresses [*Scott et al.*, 2012a; *Scott et al.*, 2012b].

30.6.2.3. Shipping

International shipping accounts for > 80% of world trade by volume [*UNCTAD*, 2009a; b] and ~3% of global CO_2 emissions from fuel combustion (IMO, 2009), although emissions are expected to increase 2-3 fold by 2050 [*UNCTAD*, 2009b]. However, increased shipping, and the concurrent increase economic activity, will increase the emission of black carbon. The black carbon will in turn increase warming and ice-melt that further increases economic activity and shipping [*Lack and Corbett*, 2012]. Changing shipping routes [*Borgerson*, 2008], shifts in grain production and global markets, as well as new fuel and weather-monitoring technology, may alter these emission patterns. Higher temperatures and extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damage infrastructure, and introduce additional dangers to ship, crew and the environment [*UNCTAD*, 2009a; b].

Climate change may benefit maritime transport by reducing Arctic sea ice, shortening sailing distances between key ports [*Borgerson*, 2008] and thus decreasing total GHG emissions from ships. Currently, reliability of this route limits its use [*Schøyen and Bråthen*, 2011], and the potential full operation of the Northwest Passage and Northern Sea Route would require a transit management regime, regulation (e.g. navigation, environmental, safety and security) and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interests in the Arctic.

30.6.2.4. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry is a key driver of energy and climate scenarios due to its role in supplying the liquid fossil fuels that are key contributors to greenhouse gas emissions. The industry also faces potential impacts from climate change on its ocean-based activities. Over 100 oil and gas platforms were destroyed in the Gulf of Mexico by the unusually strong hurricanes, Katrina and Rita. Other impacts to oil pipelines and production facilities ultimately reduced US refining capacity by 20% (AR5 SREX). The increasing demand for oil and gas has pushed operations to waters 2,000 m deep or more, far beyond continental shelves. The very large-scale moored developments involved are exposed to greater hazards and higher risks, most of which are not well understood by existing climate/weather projections. Although there is a strong trend towards seafloor well completions with a complex of wells, manifolds and pipes that are not exposed to surface forcing, these systems face different hazards from instability and bottom scouring from deep sea currents of the unconsolidated sediments [*Randolph et al.*, 2010]. Impacts from warming oceans on sea floor stability are widely debated due largely to uncertainties about the effects of methane and methane hydrates [*Archer et al.*, 2009; *Geresi et al.*, 2009; *Sultan et al.*, 2004]. The principle threat to oil and gas extraction in maritime settings is the impact of extreme weather on oil and gas extracting infrastructure [*Kessler et al.*, 2011], and this threat is likely to increase given that future storm systems are expected to have greater energy [*Emanuel*, 2005; *Knutson et al.*, 2010; *Trenberth and Shea*, 2006]. Events such as Hurricane Katrina in 2005 have illustrated challenges likely to arise for this industry with projected increases in storm intensity [*Cashell et al.*, 2005; *Cruz and Krausmann*, 2008]. In this regard, early warning systems and preparation planning offer some potential to reduce the impact of extreme events [*IPCC*, 2012].

30.6.3. Health and Social Vulnerability

30.6.3.1. Disease

Changing patterns of disease, water and food security, human settlements, extreme climatic events, and population growth and migration are the major threats to public health related to climate change [*Costello et al.*, 2009]. Evidence of linkages between climate change, the Ocean and disease are *limited*, although there is *medium agreement* that climate change has and will influence the frequency and incidence of disease in corals, molluscs and a range of other invertebrates [*Bruno et al.*, 2007; *Harvell et al.*, 2002a]. The predominately negative impacts are likely to be more serious in low-income countries such as southeast Asia, southern and east Africa, and various sub-regions of South America [*Patz et al.*, 2005], countries which also have under-resourced health systems [*Costello et al.*, 2009]. Many of the influences are directly or indirectly related with basin-scale changes in the Ocean (e.g.

temperature, rainfall, plankton populations, ocean circulation; 11.2.5.1)[*McMichael et al.*, 2006], which include the spread of pathological diseases, seafood diseases, biological invasion and ballast-water discharge. Climate change impacts on the Ocean may influence the distribution of vector-borne diseases like Cholera, malaria and salmonella. The frequency of cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens show correlated multi-decadal fluctuations of ENSO and plankton blooms which may provide insight into how these disease may change with projected rates of ocean warming (11.2.5.1, [*Colwell*, 1996; *Myers and Patz*, 2009; *Pascual et al.*, 2000; *Patz et al.*, 2005; *Rodo et al.*, 2002]. The incidence of diseases such as ciguatera also shows a link to ENSO, with ciguatera becoming more prominent after periods of elevated sea temperature (e.g. ENSO). This indicates that ciguatera may become more frequent in a warmer climate [*Llewellyn*, 2010].

30.6.3.2. Security of Social Benefits and Fisheries

Climate change impacts on open-ocean fish populations are expected to affect the economics of fishing and the livelihood security of fishing nations because of changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labour markets, and industry re-organisation [*Sumaila et al.*, 2011]. A study of the potential vulnerabilities of national economies to the effects of climate change on fisheries concluded that Malawi, Guinea, Senegal, Peru, Columbia, Bangladesh, Cambodia, Pakistan, and Yemen are most vulnerable [*Allison et al.*, 2009]. In contrast, countries at high latitudes are likely to experience increases in their potential fisheries catch [*Cheung et al.*, 2010] although there are many uncertainties (*medium confidence*; 30.5.1). Fisheries provides 50 to 90% of dietary animal protein in rural areas of many Pacific countries, providing up to 20% of the GDP of some countries, with licence fees from foreign fishing fleets providing up to 40% of government revenue [*Bell et al.*, 2013a]. Tuna are very responsive to changing sea temperatures. In the western equatorial Pacific, nations with the greatest dependence on tuna fisheries (e.g. Kiribati, Nauru, Tuvalu, Tokelau) are likely to benefit as tuna distributions shift eastward as global and ocean temperature change [30.5.1]. Climate change on the other hand will decrease food security through impacts on fisheries associated with coral reefs and mangroves (estimated loss of 20% by 2050)[*Bell et al.*, 2013a].

30.6.4. Ocean-Based Mitigation

30.6.4.1. Deep Sea Carbon Sequestration

The economic impact of deliberate CO_2 sequestration beneath the sea floor has earlier been reviewed [*Metz et al.*, 2005]. Active CO_2 sequestration from co-produced CO_2 into sub-sea geologic formations is proceeding in the North Sea, and in the Santos Basin offshore Brazil. It is likely that these activities will increase as off shore oil and gas production increasingly produces fields with high CO_2 in the source gas and oil. Significant risks from the injection of high levels of CO_2 into deep ocean waters have been identified for deep sea organisms and ecosystems. These risks are similar to those discussed previously with respect to ocean acidification and are also likely to exacerbate declining oxygen levels and trophic networks in deep water areas [*Seibel and Walsh*, 2001].

There are significant issues within the decision frameworks regulating these activities. Dumping of any waste or other matter in the sea including the seabed and its subsoil is strictly prohibited under the 1996 London Protocol (LP) except for those few materials listed in Annex I. The direct injection of CO_2 into sub-surface geological formations is generally considered to fall under the exception to the definition of "dumping" under the LP as "placement for a purpose other than the mere disposal thereof." The LP was amended in 2006 to permit storage of CO_2 under the seabed. Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-Seabed Geological Formations were adopted by the parties to the LP in 2007. The Guidelines take a precautionary approach to the process requiring Contracting Parties under whose jurisdiction or control such activities are conducted to issue a permit for the disposal subject to stringent conditions being fulfilled [*Rayfuse and Warner*, 2012].

30.6.4.2. Blue Carbon: Sequestering and Maintaining Carbon in Marine Ecosystems

Marine and coastal ecosystems such as mangroves and salt marsh store significant amounts of organic carbon, which has been referred to as 'Blue Carbon' by analogy to the ocean equivalent of sequestered carbon within forests and other terrestrial ecosystems ('green carbon'). The measurements and recognition of the carbon sequestration value of marine ecosystems is in its infancy but may assume importance given that significant amounts of organic carbon are stored within ocean ecosystems such as sea grass beds and mangroves (e.g. sequestered carbon per square metre of mangrove is many times that of terrestrial forests). Assuming that the global trade in carbon matures, the strategy to protect and expand the sequestration of carbon within marine ecosystems may play an essential role in reducing the current higher flux of greenhouse gases such as carbon dioxide and methane to the atmosphere [*Mcleod et al*., 2011].

30.6.5. Maritime Security and Related Operations

Climate change and its influence on the Ocean has become an area of increasing concern in terms of the maintenance of national security and the protection of countries' citizens. These concerns have arisen as Nation States increasingly engage in operations ranging from humanitarian assistance in climate change related disasters to territorial issues exacerbated by changing coastlines, human communities, resource access and new seaways [*Kaye*, 2012; *Rahman*, 2012]. In this regard, increasing sea levels along gently sloping coastlines can have the seemingly perverse outcome that the territorial limits to the maritime jurisdiction of the State might be open to question as the distance from national baselines to the outer limits of the exclusive economic zone increases beyond 200 nm over time [*Schofield and Arsana*, 2012].

Changes in coastal resources may also be coupled with decreasing food security to compound coastal poverty and lead, in some cases, to increased criminal activities such as piracy, illegal fishing, and people smuggling and arms and drug trafficking [*Kaye*, 2012]. While the linkages have not been clearly defined in all cases, it is very likely that changes in the Ocean as result of climate change are likely to increase pressure on resources aimed at maintaining maritime security and countering criminal activity, disaster relief operations, and freedom of navigation. The size and shape of maritime security infrastructure may also require rethinking as new challenges present themselves as a result of climate change [*Rahman*, 2012]. Opportunities may also arise from changes to international geography such as formation of new ice free seaways through the Arctic, which may benefit some countries in terms of maintaining maritime security and access. On the other hand, new features such as these within the Ocean may also lead to increasing international tensions as States perceive new vulnerabilities from these changes to geography.

Like commercial shipping (30.6.2.3), Naval operations in many countries emit significant greenhouse emissions (e.g. US Navy emits around 2% of the national greenhouse gas emissions), [*Mabus*, 2010]. As a result, there are a number of substantial programs within navies around the world to reduce their greenhouse footprint through improved engine efficiency, reducing fouling of vessels, increasing the use of biofuels and nuclear technology for power generation, and other strategies. The push to reduce emissions by using renewable fuel sources has the very substantial and synergistic benefit of increasing independence from foreign sources of energy [*Rahman*, 2012].

30.6.6. Multi-Sector Synthesis, and Key Risks and Vulnerabilities

The Ocean interacts with almost all aspects of life on Earth. As a result, it is not instructive to assess the impacts of climate change on the Ocean as a series of isolated influences and impacts on sub-regions and sectors. Many aspects of the Ocean's chemical and physical characteristics are changing rapidly, triggering high levels of change within the Ocean's ecosystems. Given the direct dependence of hundreds of millions of people on ocean ecosystem services, many of the aspects of the changes discussed as part of this chapter are *very likely* to increase the risk of poverty, decrease food security, and increase social and economic dysfunction along coastlines throughout the world. At the same time, industries such as fishing and shipping will face increasing uncertainty concerning conditions within the Ocean, which may offer opportunities (e.g. increased access to Arctic resources and sea lanes) as well as significant challenges (e.g. rapidly moving and changing fisheries resources). Impacts from climate change are also *very likely* to interact with stressors not related to anthropogenic climate change. These changes may

be antagonistic (i.e. dampening the influence of each change) or synergistic, amplifying the influence that each change would have had on its own. Our understanding of these interactions and how they will play out under rapid climate change is incomplete and uncertain. A better understanding of these interactions between climate change and other human related stressors is, consequentially, of central importance to the understanding of how we might adapt to the changes that are occurring and will occur within the Ocean.

Key risks and vulnerabilities due to climate change across ocean sectors are synthesised in Table 30-6 and range from changing ocean productivity, ecosystem regime shifts, migration of organisms and ecosystems, reorganisation of fisheries composition, increases in disease and invading organisms, and the impacts of sea level rise and changing weather patterns on coastal processes, industries, and people. In addition to these risks and vulnerabilities, are the important implications of sea level rise and the loss of summer sea ice for the definition of maritime zones and aspects of national security. Issues have been discussed in previous chapters and section of the present chapter. The ramifications of these changes are also outlined in Table 30-6 including impacts on human communities and industries associated with coastal and oceanic sectors from fishing and tourism to maritime security.

30.6.7. Global Frameworks for Decisionmaking

As outlined here, there is little credible doubt that the Ocean is changing fundamentally as a result of the activities of humans at local and global scales (*very high confidence*). We are only just beginning to understand both the scale and complexity of these changes, highlighting the critical importance of rapidly reducing the emissions of greenhouse gases while at the same time seeking strategies to reduce the impact of changing physical and chemical circumstances and ecosystems across the planet. In the latter case, strong frameworks for global decision-making are critical for devising and implementing adaptation and mitigation strategies for reducing the impacts of climate change (Table 30-6, column 6). These frameworks if they continue to be successful, represent opportunities for global cooperation and the development of international, regional and national policy responses to the challenges posed by the changing ocean [*Kenchington and Warner*, 2012; *Tsamenyi and Hanich*, 2012; *Warner and Schofield*, 2012].

[INSERT TABLE 30-6 HERE
Table 30-6: Key risks and vulnerabilities, as well as ramifications, adaptation options and frameworks for decision-making within a number of areas discussed in chapter 30. Symbols are as follows: T = sea temperature; UW = upwelling; OA = ocean acidification; NU = nutrient concentration; IC = ice cover; SS = storm strength, SLR = sea level rise (↑ = Increased; ↓ = decreased; italics = uncertain). Acronyms are: CBD (Convention on Biological Diversity), CTI (Coral Triangle Initiative), GEF (Global Environment Facility), IHO (International Hydrographic Organization), ILO (International Labour Organisation), IOM (International Organisation of Migration), ISPS (International Ship and Port Facility Security), LOSC (1982 Law of the Sea Convention), MARPOL (International Convention for the Prevention of Pollution From Ships), PACC (Pacific Adaptation to Climate Change Project), PEMSEA (Partnerships in Environmental Management for the Seas of East Asia), RFMO (Regional Fisheries Management Organisations), SPREP (Secretariat of the Pacific Regional Environment Programme), UNCLOS (United Nations Convention on the Law of the Sea), UNHCR (United Nations High Commissioner for Refugees), and WHO (World Health Organisation).]

The United Nations Convention on the Law of the Sea (LOSC) was a major outcome of the third UN Conference on the Law of the Sea (UNCLOS III). The European Union and 164 countries have joined in the Convention although it is uncertain as to the extent to which the Convention codifies international maritime law. LOSC replaced earlier frameworks that were built around the 'freedom of the seas' concept and which limited territorial rights to 3 nm off a coastline. It provides a comprehensive framework for the legitimate use of the ocean and its resources, including maritime zones, navigational rights, protection and preservation of the marine environment, fishing activities, marine scientific research, and mineral resource extraction from the deep seabed beyond national jurisdiction. The relationship between climate change and LOSC is not clear and depends on interpretation of the key elements within the UNFCCC and Kyoto Protocol [*Boyle*, 2012]. However, the LOSC provides mechanisms to help structure adaptation in response to challenges posed by climate change. In a similar way, there is a wide range of other policy

and legal frameworks that structure and enable responses to the outcomes of rapid anthropogenic climate change in the oceans.

Global frameworks for decision-making are increasingly significant in the case of ocean areas, most of which fall outside national boundaries [*Elferink*, 2012; *Warner*, 2012]. While around 50% of the Earth's surface is occupied by ocean resources that are outside the exclusive economic zones and continental shelves of the world's nations (high seas and deep seabed beyond national jurisdiction), there are increasing calls for more effective decision frameworks aimed at regulating fishing and other activities (e.g. bioprospecting) within these ocean 'commons'. These international frameworks will become increasingly valuable as nations respond to changing fisheries resources and the state of ocean ecosystems that stretch across national boundaries. One such example is the multilateral cooperation that was stimulated by President Yudhoyono of Indonesia in August 2007 that led to the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI) which involves region-wide (involving 6.8 million km^2 including 132,000 km of coastline) cooperation between the governments of Indonesia, Philippines, Malaysia, Papua New Guinea, Solomon Islands and Timor Leste on reversing the decline in coastal ecosystems such as coral reefs [*Clifton*, 2009; *Hoegh-Guldberg et al.*, 2009; *Veron et al.*, 2009]. Given that coral reefs, mangroves and key resources such as tuna stocks stretch across national boundaries, partnerships such as that begun in Southeast Asia have the potential to provide key frameworks to address issues such as interaction between the over-exploitation of coastal fishing resources and the recovery of reefs from mass coral bleaching and mortality, and the implications of the movement of valuable fishery stocks beyond waters under national jurisdiction. The recently announced World Bank Global Partnership for Oceans announced (March 28, 2012) aims to create a global framework in which to engage governments, international organisations, civil and public sector interests in both understanding and finding solutions to key issues such as overfishing, pollution, and habitat destruction [*GPO*, 2012]. Similarly, the Areas Beyond National Jurisdiction (ABNJ, Global Environment Facility) Initiative has been established to promote the efficient, collaborative and sustainable management of fisheries resources and biodiversity conservation across the open ocean.

Global partnerships are also essential for providing support to many nations that often do not have the scientific or financial resources to solve the challenges that lie ahead [*Busby*, 2009; *Mertz et al.*, 2009]. In this regard, international networks and partnerships are particularly significant in terms of assisting nations in developing local adaptation solutions to their ocean resources. By sharing common experiences and strategies through global networks, nations have the chance to tap into a vast array of options with respect to responding to the impacts of climate change on global resources.

30.7. Concluding Remarks: Emerging Issues, Data Gaps, and Research Needs

Our understanding of the changes that are occurring within the Ocean as a result of climate change is still forming, as is our ability to predict how future changes will unfold. We have *very high confidence* that many aspects of the Ocean have and will change over the coming decades in response to increasing levels of greenhouse gases in the atmosphere. The high rates of change in key variables such as temperature, pH, carbonate chemistry and oxygen levels (30.3) are *virtually certain* to drive fundamental changes in ocean ecosystem structure and function.

30.7.1. Major Conclusions

There is *robust evidence, high agreement and high confidence* that the physical, chemical and biological characteristics of the Earth Ocean are changing rapidly as a result of human activities that have increased the atmospheric concentrations of greenhouse gases such as carbon dioxide (30.3-30.5). Many of these changes are large-scale, interconnected and have no analogue in thousands if not millions of years (*very high confidence*), and involve changes to the physiology and ecology of the ocean, as well as ecosystem processes such as primary productivity, marine calcification and gas exchange (*high confidence*). A comprehensive analysis of recent literature, for example, reveals that 84% of recent changes reported in the peer-reviewed scientific literature are consistent with changes expected under climate change (*high confidence*). Organisms are rapidly moving to higher latitudes with 'mobile' organisms (phytoplankton, zooplankton and fish) moving at the most rapid rates (Figure 30-

11B). At the same time, seasonal changes that drive key events in organism life cycles are advancing by 2-5 days.decade^{-1}. These changes approach and exceed in many cases those seen for terrestrial organisms and ecosystems. These fundamental changes suggest increasing asynchrony between organisms and their competitors and food, as well as the increasing likelihood of ecosystem assemblages that have no recent analogue.

Many ocean sub-regions (e.g. SES, EBUE, EUS, and STG) are experiencing changes in the extent to which upper ocean waters mix with deeper layers (*high confidence*, Box 30-1). These changes affect the supply of nutrients to the surface waters in the ocean, and have serious ramifications for the primary production of ocean ecosystems as well oxygen concentrations in many parts of the ocean (*high confidence*). In several of the world's semi-enclosed oceans (Baltic, Black, and Mediterranean Seas), ocean warming is leading to greater water column stability, which in turn has reduced mixing and primary productivity, leading to increased hypoxia at depth. In the EBUE sub-regions, however, increasing wind strength may be driving increased upwelling and consequently greater levels of primary productivity. In the latter case, however, higher levels of primary productivity and a subsequently higher flux of organic carbon into the deep ocean is resulting in reduced oxygen levels at depth. While we do not have a complete understanding of the changes to the oxygen content of the Ocean, changes in such a fundamental variable should be of great concern.

Our understanding of the influence of climate change on ocean systems has been challenged by variability which operates on a variety of spatial and temporal scales, and which can amplify the impacts of ocean warming and acidification. While most ocean regions have experienced significant changes a few regions have not. Short to long-term patterns of variability such as ENSO, PDO, AMO and NAO have complicated the interpretation of recent changes within the ocean. Despite this variability, there is an undeniable trend in ocean temperature and the response of key marine organisms and ecosystems.

The impacts and implications of the current changes in the ocean differ from sector to sector. In many parts of the world, fisheries such as those associated with tropical coastlines are expected to continue to decline. In other regions, the distribution and abundance of key fish stocks such as tuna will change over time impacting fishing industries in regions such as the Pacific and Indian oceans. Some regions may benefit while others may find it increasingly hard to obtain fish stocks as they move to new parts of the Ocean in response to changing sea temperatures. HLSBS are critically important to 36% of the world's fisheries. Fundamental changes as a result of ocean warming and acidification are occurring in the composition of plankton communities which are driving changes to the species composition and abundance of key fisheries (30.14 B). Ecological regime shifts have occurred with substantial impacts on key fisheries and dependent industries (Figure 20.15B), and are *very likely* to continue as warming continues. Climate change may lead to greater productivity in some fisheries through warmer temperatures, increased upwelling and reduced sea ice.

The economic well-being of sectors such as tourism is *very likely* to be strongly influenced by changes in regional weather patterns, rising sea levels, extreme events and the perception of risk. In addition to changing weather patterns, heat stress events such as mass coral bleaching and mortality are likely to increase as temperatures increase, bringing the future of the highly productive coastal ecosystems such as coral dominated coral reefs into question (Figure 30-12; Box CC-CR). The impacts of losing these highly productive and biologically diverse ecosystems is *likely* to change the tourist attractiveness of some regions as well is the livelihoods of millions of people that live in close association with the world's coastal areas.

There are numerous other consequences of climate change on the Ocean. In some cases, there may be advantages for international shipping from warmer and less ice-prone waters. On the other hand, sectors such as fishing and tourism will have to deal with a greater level of uncertainty and change, which has ramifications for human health and security, as well as current and future tourist opportunities. The changing conditions within the world oceans also represent challenges for industries intent on exploiting offshore energy and mineral resources. Increasing storm strength along with larger wave heights and wind velocities present increasing risks to these industry sectors. These changes in turn impact maritime security operation as well as the capacity of these elements to respond to environmental impacts associated with anthropogenic climate change.

30.7.2. Emerging Themes

The rapid changes that have been observed within the world oceans are an emerging theme within our understanding of climate change. Until recently, the impacts of climate change on ocean systems gained much less attention than those being observed within terrestrial areas of the planet. From the detection and attribution analysis undertaken here, however, it should be clear that fundamental changes in the physical, chemical and biological characteristics of the ocean are occurring rapidly and have implications for people everywhere.

The decrease in the concentration of oxygen within the ocean core and across many parts of the ocean is an emerging theme. The decrease in oxygen levels is a consequence of warming and stratification of the water column in some areas, changes in local weather patterns in others, and temperature influences on the ratio of rate of metabolism. The decline in oxygen concentrations in large parts of the ocean is of great concern given the potential impacts that spreading hypoxia could have for marine species and ecosystems. In this respect, projected increases in sea temperature under the current Business-As-Usual scenarios are likely to rapidly enhance water column stratification, increase bacterial metabolism and consequently drive major expansion in deep-ocean areas that are currently low in oxygen. Based on the impacts experienced so far from the 0.8°C increase in average global temperature, future changes are *very likely* to threaten many significant ocean ecosystems and fisheries. There are also fundamental implications for the ability of the ocean to provide planetary services such as maintaining the oxygen content of the atmosphere.

The changes in wind stress and ocean-atmosphere exchange is another emerging theme. Changes to water column mixing and ventilation have driven changes to productivity and other aspects such as oxygen concentration in a number of key areas of the world's oceans. While there is considerable discussion about how climate change will affect upwelling systems, there is concern that changes to the increase in land-ocean thermal gradient could result in stronger upwelling in some areas while others decrease (Figure 30-15). At present, there is little information and understanding about the response of these important areas of fisheries production in the rapidly warming world.

The impacts of ocean acidification on marine organisms and ecosystems (Box CC-OA) has emerged as a major concern especially given the robust evidence that the current chemistry of the ocean is outside where it has been for at least 1 million years. At current rates of increase atmospheric CO_2, the acidity of the ocean will surpass any seen over the last 40 million years [*Hoegh-Guldberg et al*., 2007; *Raven et al*., 2005]. The growing literature from the past five years has increasingly documented a major array of changes from the reduced calcification of coral reefs and pteropods, to impacts on animal reproduction, navigation, and olfaction. Ocean acidification is rapidly emerging as a very serious yet uncharted risk for all ocean sub-regions, although the earliest demonstrated impacts of changing pH and carbonate ion concentrations are being felt at higher latitudes due to the colder temperatures and hence greater flux of CO_2 entering these waters.

Understanding how the productivity of the Ocean is likely to change in a warmer and more acidic ocean is a significant emerging theme. Changes to the physical and chemical nature of ocean waters are also driving changes in the distribution and abundance of primary production (Figures 30.15, 30.15). These changes are beginning to have fundamental and large-scale influences on the distribution and abundance of primary productivity, which has implications for both fisheries as well as the flux of organic carbon into the deep ocean. While the current decreases in productivity that have been reported in the major ocean basins need to be considered in the light of natural climate variability such as ENSO and PDO, it is necessary that we develop a greater understanding of the potential implications of these rapid changes in ocean productivity. In this respect, a serious decrease in ocean services may be underway if ocean productivity continues to decrease over and above the background variability within the ocean climate systems. Extending these changes over the coming decades and century would be the basis for serious global concern. In combination with changes to sea temperature, changes to the distribution of ocean productivity has serious implications for the productive pelagic top predator fisheries that many countries depend on (30.5.2, 30.5.6; Figure 30-15). Understanding these current changes should be an urgent priority of the international community.

30.7.3. Research and Data Gaps

Despite the fact that Earth is dominated by the Ocean, we are only beginning to understand the physical, chemical and biological processes that underpin its ability to provide a range of ecosystem and planetary services. This situation has arisen because of the relative difficulty of accessing ocean environments, which has meant that comprehensive measurements of many parameters and ocean regions have only been available for the past 50 years or less. Given the importance of the world's oceans, it is an imperative that we increase our understanding of how climate change (including ocean acidification) are likely to influence the structure and function of ocean systems.

Understanding how wind stress will change in a warmer world is particularly important given the role of wind in water column mixing and nutrient availability, and hence primary and fisheries production. This gap in our understanding is crucial given the reliance of humans on the fisheries associated with upwelling regions throughout the world. Similarly, improving our understanding of the changes that are occurring within the STGs of the major ocean basins is especially significant given the strong background influence of short to long-term natural climate variability such as ENSO, PDO, and AMO. Understanding how the variability that key fisheries currently face interacts with ocean warming and acidification represents a significant knowledge and research gap.

The deep ocean below 1000 m is the most abundant habitat on the planet yet it is the region about which we know the least. In this respect, increasing our understanding of deep-ocean habitats and how these may be changing under the influence of both climate change and non-climate change factors is of great importance. Linkages between changes occurring in the surface layers of the ocean and those associated with deep regions of the world's oceans are particularly important in the light of understanding how rapidly changes are occurring as well as implications for the metabolic activity and oxygen content of deep water habitats.

While research focused on the responses of marine ecosystems to climate change has increased substantially over the past decade, much of this effort is clustered in particular sub-regions (North Pacific and North Atlantic Oceans). It will be essential to expand the number and geographical spread of studies focused on how the Ocean and its ecosystems are changing with respect to global warming and acidification. Equally, many organisms are underrepresented in the studies. Bony fish, copepods and sea birds have received a lot of attention in the scientific literature (albeit located in heavily studied sub-regions), while macroalgae (particularly brown algae), benthic invertebrates (e.g. molluscs, barnacles, cnidarians), and dinoflagellates have been the focus of a moderate number of studies. Many other organisms have not received much attention, illustrating the need for an expansion of the focus of future studies to include these organisms, which are often crucial within ocean ecosystems and processes.

We are also in an early stage of understanding of how sectors such as fishing are likely to be affected by the current fundamental changes to the Ocean. In this respect, it is highly likely that the current structure, distribution, and abundance of fishery stocks and industries are going to be transformed as we head towards a much warmer world. Developing a better understanding of how to adapt fisheries infrastructure and strategy to these changing conditions is of enormous importance. In the broadest setting, it is an imperative that we also develop a greater understanding of how changes to storm strength, sea level and a range of other factors are going to influence other activities such as shipping, energy and mineral extraction, and other human activities, especially those located in the populous coastal sub-regions of the world.

Lastly, the current expansion of technologies that can allow the automated exploration of the ocean represents a very significant opportunity to rapidly improve our understanding of one of the most fundamentally important features of our planet. Given that our understanding of how ocean systems will respond to increased greenhouse gas concentrations has lagged behind our understanding of terrestrial and atmospheric change, it is vital that these new technologies be applied at a scale which can begin to understand and project how ocean systems are likely to change over the coming decades and century. When combined with the increasing opportunities offered by satellite-based remote sensing as well is an increasing set of research activities at all depths within the ocean, these technologies represent a significant opportunity to understand both our planet and the changes on it due to human activities. Hopefully these new insights and understanding will assist humanity to not only understand but ultimately solve the massive challenges presented by anthropogenic climate change (including ocean acidification) for the world’s Ocean.

Frequently Asked Questions

FAQ 30.1: Can we reverse the climate change impacts on the ocean?

Greenhouse gas emissions have resulted in major physical and chemical changes in our oceans. In less than 150 years, we have caused changes in the oceans not seen for millions of years. These changes can be reversed if emissions are stopped, but not in our lifetime. Oceans are warming slower than land because of their higher heat capacity and the slow mixing of warmer surface waters into the deep ocean (~2,000 yr). These different characteristics of the ocean mean that it will take centuries for ocean warming to reverse once greenhouse gas emissions are reduced. As CO_2 enters the oceans it also alters ocean chemistry (reducing pH). Chemical changes to the ocean will take thousands of years to reverse.

FAQ 30.2: How can we use non-climate factors to manage climate change?

Natural systems are exposed to a range of climate change and non-climate factors. We need to manage the combined impacts of climate and other human activities such as pollution, eutrophication, habitat destruction, invasive species and fishing. These activities combine in different ways with climate change, with some acting in opposition (antagonistic) while others act together to produce an enhanced effect (synergistic). Where we find synergistic interactions, we can devote our management efforts to reducing the non-climate activities thus minimizing degradation of natural systems. For example, maintaining coastal water quality will partially alleviate the impact of thermal stress and aid recovery of seagrass beds. Identifying the type of interactions between climate and human activities will be crucial for managing climate change impacts on natural systems. Developing ecosystem-based management of fishery resources where climate-induced changes in the productivity are implemented will help maintaining sustainable fishery under climate change.

FAQ 30.3: Does slower warming mean less impact on plants and animals?

The opportunities for adapting and accommodating climate change are generally higher at slower rates of environmental change. However, there are now many observations which suggest that even small amounts of warming will lead to significant changes in the structure and function of marine ecosystems. Despite less warming in equatorial sub-regions than elsewhere, many tropical species are under threat from future warming as they are already near their upper thermal tolerance limits. Similarly, despite slower warming over ocean than land, bands of equal temperature (isotherms) are migrating polewards at similar or faster rates in the ocean implying that marine species will have to move at rates comparable to, or faster than, land species to track thermal environments. Rates of change in seasonal temperature peaks are also similar over ocean and land, implying comparable shifts in timing of life history events such as earlier reproduction in spring. Therefore, even the slower warming in the tropics and in the oceans will pose challenges to species and reorganize natural systems.

FAQ 30.4: How will marine primary productivity change?

Changes in marine primary productivity in response to climate change remain the single biggest uncertainty in predicting the magnitude and direction of future changes in fisheries and marine ecosystems. Drifting microscopic (1-100 μm) plants known as phytoplankton are the dominant marine primary producers. Their photosynthetic activities provide approximately half the oxygen we breathe, supports most marine food webs, and influences global biogeochemical cycles. There is considerable uncertainty in observed changes in primary production globally, with some studies showing declines and others increases. Regionally, there is mounting evidence of productivity increases in the world's most productive (upwelling) systems, some evidence that productivity in the highest latitudes of the spring-bloom ecosystems and polar areas is increasing. Longer satellite time series, maintenance of in-water time series, and more emphasis on modeling future primary productivity are needed.

FAQ 30.5: Can we expect actual loss of marine life and/or the creation of true ocean dead zones under climate change?

Warming of the ocean by 2 degrees will reduce oxygen solubility by about 14 micromoles per kg at typical mid-water temperatures (5º - 7ºC). In some areas of the ocean such as those at a few hundred meters depth off the west coast of the Americas, and in the northern Arabian Sea, where oxygen levels are already low, we may expect conditions in which oxygen is virtually zero, with resulting loss of life. A smaller additional ocean oxidation

capacity is represented by the presence of dissolved nitrate which can be used by bacteria as a chemical resource thus delaying the absolute loss of oxygen. This process is occurring regionally today, and oceanic nitrate losses occurred in the pre-industrial ocean. But the combined oxidation capacity of oxygen and nitrate will be exceeded, and once this occurs, toxic hydrogen sulfide can appear in the ocean water column. This has not been seen in recorded history although short term sporadic eruptions of sulfide from the sea floor have been observed. There is evidence for the presence of sulfide oxidizing bacteria in the sub-oxic ocean today. The reduction of dissolved oxygen from solubility effects alone greatly underestimates the case. Ocean data shows that only ~15% of the observed changes can be attributed to solubility reduction from warming; ~85% is attributable to the effects of increased bacterial activity and reduced ventilation by the atmosphere in the more stratified upper ocean. If these trends hold then ~5x greater oxygen losses could occur at depth with more widespread true dead zones at depth and loss of marine life in affected ocean regions.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

[Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]

Coral reefs are shallow-water structures made of calcium carbonate mostly secreted by reef-building (scleractinian) corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics. About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and are likely to derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including those from provisioning (food, construction material, medicine), regulating (shoreline protection, water quality), supporting services (oxygen supply) and cultural (religion, tourism). This is especially true in small islands (29.3.3.1).

Most human-induced disturbances to coral reefs were local (e.g., coastal development, pollution, nutrient enrichment and overfishing) until the early 1980s when global and climate-related disturbances (ocean warming and acidification) began to occur. Temperature and seawater acidity are two of the most important environmental variables determining the distribution of coral reefs (Kleypas et al., 2001). As corals are centrally important as ecosystem engineers (Wild et al., 2011), the impacts on corals have led to widespread degradation of coral reefs.

A wide range of climatic and non-climatic stressors affect corals and coral reefs and negative impacts are already observed (5.4.2.4, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae (genus *Symbiodinium*), which live in the coral tissues and play a key role in supplying the coral host with energy and nutrients (Baker et al., 2008) (see 6.2.5 for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies, is the most widespread and conspicuous impact (Fig. 5X; see Sections, 5.4.2.4, 6.2.5, 25.6.2, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Elevated temperature along with ocean acidification reduces the calcification rate of corals (*high confidence*; 5.4.2.4), and may tip the calcium carbonate balance of reef frameworks towards dissolution (*medium evidence and agreement*; 5.4.2.4). These changes will erode fish habitats with cascading effects reaching fish community structure and associated fisheries (*robust evidence, high agreement*, 30.5).

Around 50% of all coral reefs have experienced medium-high to very high impact of human activities (30-50% to 50-70% degraded; Halpern et al., 2008), which has been a significant stressor for over 50 years in many cases. As a result, the abundance of reef building corals is in rapid decline (1 to 2% per year, 1997-2003) in many Pacific and SE Asian regions (Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and coral bleaching have led to a decline in coral cover on the Great Barrier Reef (about 51% between 1985 and 2012; De'ath et al., 2012).

One third of all coral species exhibit a high risk of extinction, based on recent patterns of decline and other factors such as reproductive strategy (Carpenter et al., 2008). Although less well documented, non-coral benthic

invertebrates are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation coral reefs, including in a marine reserve (Jones et al., 2004). While many factors, such as overfishing and local pollution, are involved in the decline of coral reefs, climate change through its pervasive influence on sea temperature, ocean acidity, and storm strength plays a very significant role.

There is *robust evidence* and *high agreement* that coral reefs are one of the most vulnerable marine ecosystems (Chapters 5, 6, 25, and 30). Globally, more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011) even in the absence of climatic factors. Future impacts of climate stressors (ocean warming, acidification and sea level rise) will exacerbate the impacts of non-climatic stressors (*high agreement*, *robust evidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9–60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation under the RCP3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30–88%, 68% uncertainty range). If present day corals have residual capacity to acclimatize and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan et al., sbm). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs produce 10-12% of the fish caught in tropical countries, and 20-25% of the fish caught by developing nations (Garcia & Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton et al. (2012) are already exploiting their coral reef fisheries in an unsustainable way (13.X.X).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4, 30.5).

Coral reefs make a modest contribution to the global domestic product but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent on average 5% of the GDP of South Pacific islands (Laurans et al., 2013). At the local scale, these two services provide at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are less effective in reducing coral loss from thermal stress (Selig et al., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012). Controlling the input of nutrients and sediment from land is an important complementary management strategy because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2012). There is also high confidence that, in the long term, limiting the amount of warming and acidity is central to ensuring the viability of coral reef systems and dependent communities (5.X.X and 30.5).

[INSERT FIGURE CR-1 HERE

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that

prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction

Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30-5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult; observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey

relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could

involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

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Table 30-1: Percent area of the ocean, primary productivity and fisheries catch (production) for major sub-regions of the ocean (for location of sub-regions, see Figure 30-1).

Ocean sub-region		Area (%)	Primary Productivity (%)*	Fishery Productivity or Long-term Fish Catches (%)**	Relevant IPCC regions (Chapters)
1. High-latitude Spring-bloom System (HLSBS)	Northern Hemisphere	10.60	22.74	29.20	*23-24, 26,28*
	Southern Hemisphere	14.40	20.55	6.82	*22, 25, 28*
2. Equatorial Upwelling Systems (EUS)		8.20	9.01	4.68	*22,27,29*
3. Semi-enclosed seas (SES)		1.12	2.35	3.28	*22,23*
4. Coastal Boundary Systems (CBS)		6.29	10.64	28.02	*22,24-26, 29*
5. Eastern Boundary Upwelling Ecosystems (EBUE)		1.80	6.97	19.21	*22,26,27*
6. Subtropical gyres (STG)		40.55	21.20	8.26	*22,24-26,29*
7. Deep Ocean (DO)***		N/A	N/A	N/A	*22-29*
8. Arctic and Antarctic System - Chapter 28		17.04	6.54	0.53	*23,24,25, 26*

* Based on Field et al. (1998)

** Average fish catches 1970-2006 Based on FAO

*** Not calculated (<0.5%)

Table 30-2: Regional changes in sea surface temperature (SST) over the past 50 years for ocean sub-regions specified in Figure 30-1. A linear regression was fitted to all 1x1 degree monthly SST data extracted from the HadISST 1.1 data set (Rayner et al., 2003) for the period of 1950 to 2009 for each ocean sub-region. The Table includes the slope of the regression ($^{o}C.decade^{-1}$), p value of the slope being different to zero, Linear Change Over 50 Years (slope of linear regression multiplied by 5 to obtain the average change over 50 years, and the difference between the mean temperature (1950-1959) from the mean temperature 50 years later (2000-2009). The latter may be different to the linear change over 50 years if there is significant long-term variability around the trend line. The last column compares the linear trend with that calculated between the two means with significant deviations (<0.8 and > 1.2) shown in red. P values that exceed 0.05 are also shown in red.

Region	Sub-region	oC/Decade	p Value	Linear Change Over 50 Years (1955-2005)	Mean (2000-2009) - Mean (1950-1959)	Index of Variability
1. High Latitude Spring Bloom Systems (HLSBS)						
	Indian Ocean	0.09	0.00	0.43	0.40	0.92
	North Atlantic	0.79	0.00	3.97	2.49	0.63
	South Atlantic	0.06	0.10	0.32	0.33	1.04
	North Pacific (west)	0.53	0.00	2.65	2.24	0.84
	North Pacific (east)	1.27	0.00	6.34	5.36	0.84
	Total North Pacific	0.92	0.00	4.62	3.90	0.84
	South Pacific (west)	0.02	0.65	0.08	0.12	1.43
	South Pacific (East)	0.03	0.40	0.15	0.25	1.60
	Total South Pacific	0.03	0.47	0.13	0.21	1.56
2. Equatorial Upwelling Systems (EUS)						
	Atlantic equatorial upwelling	0.09	0.00	0.45	0.49	1.09
	Pacific equatorial upwelling	0.07	0.00	0.35	0.24	0.67
3. Semi-Enclosed Seas (SES)						
	Arabian Gulf	0.10	0.30	0.50	0.45	0.91
	Baltic Sea	0.46	0.13	2.28	3.15	1.39
	Black Sea	0.05	0.68	0.26	0.54	2.04
	Mediterranean Sea	0.08	0.32	0.42	0.41	0.98
	Red Sea	0.07	0.14	0.35	0.36	1.03

4. Coastal Boundary Systems (CBS)						
	Western Atlantic	0.12	0.00	0.61	0.62	1.02
	GOM/Caribbean	0.02	0.50	0.12	0.10	0.81
	Western Indian ocean	0.10	0.00	0.50	0.49	0.98
	Eastern Indian Ocean	0.09	0.00	0.46	0.40	0.86
	E Indian/SE Asia/W Pacific	0.13	0.00	0.67	0.56	0.84
5. Eastern Boundary Upwelling Ecosystems (EBUE)						
	Benguela current	0.03	0.44	0.16	0.38	2.38
	California current	0.12	0.01	0.61	0.20	0.33
	Canary current	0.09	0.01	0.45	0.42	0.94
	Humboldt current	0.06	0.21	0.30	0.09	0.31
6. Subtropical Gyres						
	Indian ocean	0.11	0.00	0.56	0.53	0.94
	North Atlantic	0.05	0.28	0.23	0.21	0.92
	South Atlantic	0.08	0.02	0.42	0.47	1.14
	North Pacific (west)	0.07	0.02	0.36	0.34	0.96
	North Pacific (east)	0.04	0.13	0.21	0.14	0.66
	Total North Pacific	0.06	0.05	0.28	0.23	0.84
	South Pacific (west)	0.08	0.00	0.38	0.39	1.04
	South Pacific (East)	0.06	0.05	0.28	0.29	1.06
	Total South Pacific	0.06	0.03	0.30	0.32	1.05
7. Coral Reef Provinces (Figure 30.3)						
	Caribbean & Gulf of Mexico	0.02	0.38	0.12	0.13	1.11
	Coral Triangle & SE Asia	0.13	0.00	0.65	0.55	0.84
	Eastern Indian Ocean	0.10	0.00	0.49	0.43	0.88
	Western Indian Ocean	0.10	0.00	0.50	0.48	0.97
	Eastern Pacific Ocean	0.09	0.00	0.47	0.24	0.52
	Western Pacific Ocean	0.07	0.00	0.36	0.39	1.07

8. Basin Scale						
	North Atlantic combined	0.52	0.00	2.62	1.67	0.09
	South Atlantic combined	0.07	0.04	0.37	0.41	0.04
	Atlantic Ocean Basin	0.30	0.00	1.51	1.05	0.03
	North Pacific total	0.38	0.00	1.89	1.59	0.07
	South Pacific total	0.05	0.11	0.24	0.28	0.03
	Pacific Ocean Basin	0.20	0.00	1.01	0.88	0.02
	Indian Ocean basin	0.11	0.00	0.56	0.53	0.94

Table 30-3: CMIP-5 models used to create the Chapter 30 RCP 2.6, 4.5, 6.0 and 8.5 SST ensembles. All models indicated were used in both the ensemble SSTs as well as the production of the DHMs, with the exception of 2 model outputs, denoted by a *. These two models were included in the ensembles but not in the production of the DHMs due to issues with the development of an appropriate Maximum Monthly Mean (MMM) climatology.

CMIP-5 Model	**RCP 2.6**	**RCP 4.5**	**RCP 6.0**	**RCP 8.5**
ACCESS1-0		1		1
ACCESS1-3		1		1
BCC-CSM1-1	1	1	1	1
CanESM2	1	1		1
CMCC-CM		1		1
CMCC-CMS		1		1
CNRM-CM5	1	1		1
CSIRO-Mk3-6-0	1	1	1	1
EC-EARTH	*	1		1
FIO-ESM	1	1	1	1
GFDL-CM3	1	1	1	1
GFDL-ESM2G	1	1	1	1
GFDL-ESM2M	1	1		1
GISS-E2-R-p1	1	1	1	1
GISS-E2-R-p2	1	1	1	1
GISS-E2-R-p3	1	1	1	1
HadGEM2-AO	1	1	1	1
HadGEM2-CC		1		1
HadGEM2-ES	1	1	1	1
INMCM4		1		1
IPSL-CM5A-LR	1	1	*	1
IPSL-CM5A-MR	1	1		1
MPI-ESM-LR	1	1		1
MPI-ESM-MR	1	1		1
CESM1-BGC		1		1
CESM1-CAM5	1	1	1	1
NorESM1-M	1	1	1	1
NorESM1-ME	1	1	1	1
Number of models	**20+1***	**28**	**13+1***	**28**

Table 30-4: Projected changes in sea surface temperature (SST, ºC) over the next 90 years for Ocean sub-regions (Figure 30-1) using model runs from the Coupled Model Intercomparison Project Phase 5 (CMIP-5, http://cmip-pcmdi.llnl.gov/cmip5/). Runs were divided up into their respective Representative Concentration Pathways (RCP) to form four groups: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The CMIP-5 models that were used in this analysis are listed in Table 30.3. For each region, a linear regression was fitted to all 1x1 degree monthly SST data extracted from the models for each of three periods; 2010-2039, 2040-2069 and 2070-2099. The average change in SST was calculated by multiplying the slope of each linear regression by 360 (months) to derive the average change over each successive 30 year period. The table is divided into two sections, "Near-term (2010-2039)" – the average change in SST over the next 30 years, and "Long-term (2010-2099)" – the total change from 2010-2099, which was calculated by adding the average change of the three 30 year periods from 2010 to 2099. This is a simplified method to account for slight non-linearity in SST change over the 90 year period.

Region	Sub-region	Near-term (2010-2039)				Long-term (2010-2099)				Diff RCP8.5 - RCP2.6
		RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	
1. High Latitude Spring Bloom Systems (HLSBS)										
	Indian Ocean	0.13	0.29	0.18	0.41	-0.16	0.49	0.83	2.01	2.17
	North Atlantic	0.31	0.56	0.52	0.65	0.54	1.54	1.95	3.02	2.48
	South Atlantic	0.17	0.36	0.20	0.45	-0.09	0.67	0.88	2.26	2.36
	North Pacific (west)	0.79	0.96	0.91	1.17	1.46	2.47	3.07	4.84	3.38
	North Pacific (east)	0.79	0.81	0.93	1.06	1.31	2.17	2.96	4.39	3.08
	Total North Pacific	0.79	0.88	0.92	1.11	1.35	2.31	3.01	4.60	3.25
	South Pacific (west)	0.17	0.40	0.25	0.50	-0.16	0.63	0.85	2.37	2.53
	South Pacific (East)	0.12	0.23	0.13	0.35	-0.09	0.45	0.75	1.70	1.79
	Total South Pacific	0.14	0.28	0.17	0.40	-0.12	0.51	0.78	1.91	2.03
2. Equatorial Upwelling Systems (EUS)										
	Atlantic equatorial upwelling	0.43	0.58	0.49	0.81	0.46	1.19	1.61	3.03	2.56
	Pacific equatorial upwelling	0.35	0.55	0.54	0.77	0.43	1.22	1.75	3.01	2.57
3. Semi-Enclosed Seas (SES)										
	Arabian Gulf	0.82	0.97	0.89	1.20	1.30	2.39	2.96	4.26	2.96
	Baltic Sea	0.73	1.24	0.92	1.20	1.32	2.74	3.06	4.37	3.05
	Black Sea	0.74	1.01	0.86	1.24	1.37	2.61	3.16	4.19	2.82
	Mediterranean Sea	0.72	0.87	0.84	1.09	1.37	2.10	2.82	4.08	2.70
	Red Sea	0.56	0.72	0.71	0.93	0.88	1.65	2.39	3.45	2.57

4. Coastal Boundary Systems (CBS)										
	Western Atlantic	0.34	0.40	0.45	0.62	0.23	0.81	1.33	2.44	2.21
	GOM/Caribbean	0.50	0.67	0.64	0.85	0.74	1.53	1.97	3.23	2.49
	Western Indian ocean	0.46	0.59	0.56	0.85	0.63	1.39	1.95	3.32	2.69
	Eastern Indian Ocean	0.34	0.57	0.46	0.69	0.38	1.22	1.59	2.80	2.42
	E Indian/SE Asia/W Pacific	0.48	0.66	0.57	0.82	0.66	1.47	1.89	3.12	2.46
5. Eastern Boundary Upwelling Ecosystems (EBUE)										
	Benguela current	0.30	0.43	0.45	0.71	0.07	0.70	1.41	2.52	2.45
	California current	0.62	0.71	0.84	0.93	1.02	1.86	2.46	3.51	2.49
	Canary current	0.55	0.62	0.58	0.82	0.97	1.30	1.83	3.18	2.21
	Humboldt current	0.22	0.43	0.34	0.60	0.11	0.91	1.22	2.58	2.47
6. Subtropical Gyres										
	Indian ocean	0.30	0.44	0.37	0.63	0.19	0.89	1.35	2.62	2.43
	North Atlantic	0.49	0.66	0.60	0.85	0.87	1.62	1.98	3.30	2.43
	South Atlantic	0.25	0.33	0.33	0.55	0.03	0.58	1.03	2.20	2.18
	North Pacific (west)	0.54	0.70	0.64	0.90	0.84	1.62	2.08	3.39	2.55
	North Pacific (east)	0.56	0.66	0.71	0.91	0.90	1.56	1.50	3.44	2.54
	Total North Pacific	0.55	0.68	0.68	0.90	0.87	1.58	2.09	3.42	2.55
	South Pacific (west)	0.31	0.44	0.34	0.62	0.12	0.88	1.19	2.56	2.44
	South Pacific (East)	0.17	0.27	0.21	0.45	-0.03	0.52	0.89	1.90	1.93
	Total South Pacific	0.20	0.31	0.24	0.49	0.00	0.60	0.96	2.05	2.05
7. Coral Reef Provinces (Figure 30.3)										
	Caribbean & Gulf of Mexico	0.48	0.64	0.61	0.83	0.68	1.43	1.87	3.14	2.46
	Coral Triangle & SE Asia	0.42	0.61	0.52	0.76	0.58	1.35	1.75	2.95	2.37
	Eastern Indian Ocean	0.32	0.56	0.46	0.67	0.37	1.18	1.59	2.76	2.40
	Western Indian Ocean	0.39	0.51	0.50	0.77	0.43	1.18	1.71	2.97	2.54
	Eastern Pacific Ocean	0.46	0.64	0.64	0.83	0.63	1.44	1.99	3.23	2.60
	Western Pacific Ocean	0.35	0.48	0.40	0.68	0.30	1.02	1.39	2.66	2.35

8. Basin Scale changes										
	North Atlantic combined	0.37	0.60	0.55	0.72	0.66	1.57	1.96	3.12	2.46
	South Atlantic combined	0.21	0.35	0.27	0.51	-0.03	0.62	0.76	2.23	2.26
	Atlantic Ocean Basin	0.32	0.50	0.44	0.65	0.38	1.17	1.54	2.78	2.40
	North Pacific total	0.64	0.75	0.77	0.98	1.06	1.85	2.43	3.86	2.80
	South Pacific total	0.18	0.30	0.21	0.45	-0.04	0.56	0.89	2.00	2.04
	Pacific Ocean Basin	0.41	0.54	0.51	0.73	0.52	1.23	1.70	2.97	2.45
	Indian Ocean Basin	0.30	0.44	0.37	0.63	0.19	0.89	1.35	2.62	2.43

Table 30-5: Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from fisheries and aquaculture, and to maximize the opportunities. These measures are classified as 'win-win' (W-W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or 'lose-win' (L-W) adaptations, where benefits exceed costs in the short term but accrue under longer-term climate change (Modified from *Bell et al*. 2013a).

Adaptation options	Supporting policies
Economic development	
Full implementation of the vessel day scheme (VDS) to control fishing effort by the Parties to the Nauru Agreement[a] (W-W).	• Strengthen national capacity to administer VDS. • Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna. • Include implications of climate change in management objectives of the WCPFC. • Apply national management measures to address climate change effects for sub-regional concentrations of tuna in archipelagic waters beyond WCPFC's mandate. • Require all industrial tuna vessels to provide operational-level catch and effort data to improve models for projecting redistribution of tuna stocks during climate change.
Diversify sources of fish for canneries and maintain trade preferences (W-W).	
Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and maximize their resilience to climate change (W-W).	
Energy efficiency programmes to assist fleets to cope with oil price rises, minimise CO_2 emissions, and reduce costs of fishing further afield as tuna move east (W-W).	
Pan-Pacific tuna management through a merger of the Western and Central Pacific Fisheries Commission (WCPFC) and Inter-American Tropical Tuna Commission to co-ordinate management measures across the entire tropical Pacific (L-W).	
Food security and livelihoods	
Manage catchment vegetation to reduce transfer of sediments and nutrients to rivers and coasts to reduce damage to freshwater fish habitats, and coral reefs, mangroves and seagrasses supporting coastal fisheries (W-W).	• Strengthen governance for sustainable use of coastal fish habitats by: (1) building national capacity to understand the threats of climate change; (2) empowering communities to manage fish habitats; and (3) changing agriculture, forestry and mining practices to prevent sedimentation and pollution. • Minimise barriers to landward migration of coastal habitats during development of strategies to assist other sectors to respond to climate change. • Apply 'primary fisheries management' to stocks of coastal fish and shellfish to maintain their potential for replenishment. • Allocate the necessary quantities of tuna from total national catches to increase access to fish for both urban and coastal populations. • Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security. • Include inshore FADs as part of national infrastructure for food security, and undertake regular maintenance and replacement of FADs. • Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be 'climate-proofed' and relocated if necessary.
Foster the care of coral reefs, mangroves and seagrasses by preventing pollution, managing waste and eliminating direct damage to these coastal fish habitats (W-W).	
Provide for migration of fish habitats by: (1) prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help plants colonise landward areas as sea level rises; and (2) allowing floodplains to expand as rainfall increases (L-W).	
Sustain and diversify catches of coral reef fish to maintain the replenishment potential of all stocks (L-W).	
Increase access to tuna and by-catch caught by industrial fleets through storing and selling these fish at major ports to provide inexpensive fish for rapidly growing urban populations (W-W).	
Install fish aggregating devices (FADs) close to the coast to improve access to tuna and other large pelagic fish for rural communities as human populations increase and coral reef fish decline (W-W).	
Improve simple post-harvest methods to extend the shelf life of fish when good catches are made (W-W).	
Relocate pearl farming operations to deeper water and sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for growth and survival of pearl oysters, and formation of high-quality pearls (L-W).	

a = The Parties to the Nauru Agreement (PNA) are Palau, Federated States of Micronesia, Papua New Guinea, Solomon Islands, Marshall Islands, Nauru, Kiribati and Tuvalu.

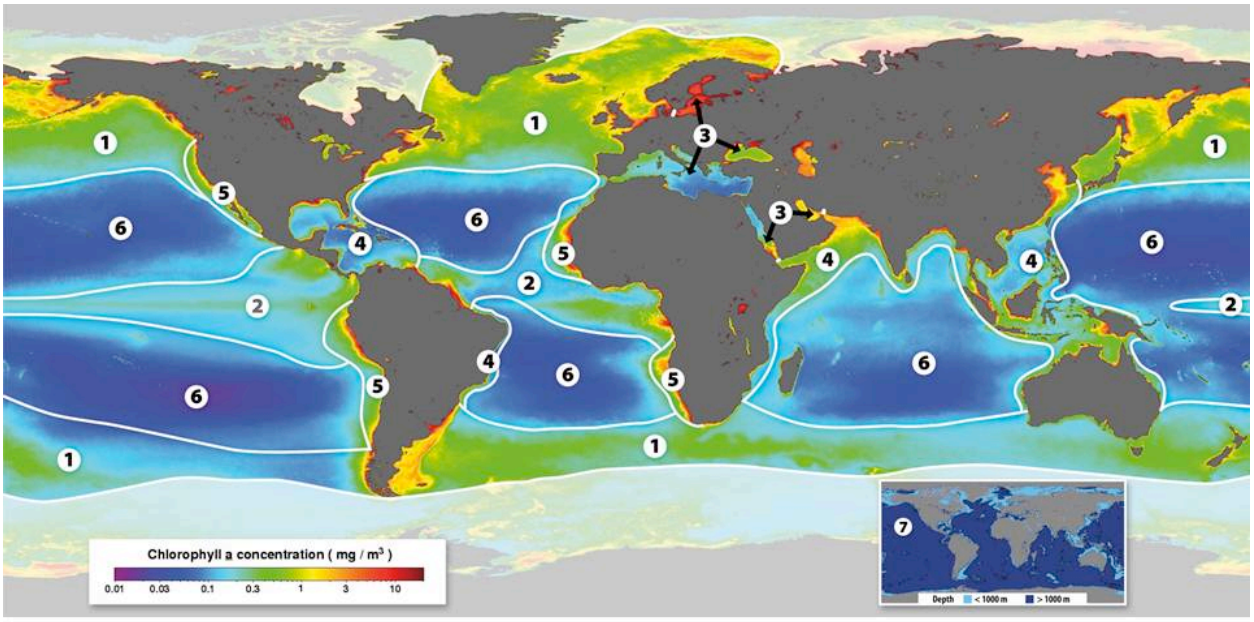
Table 30-6: Key risks and vulnerabilities, as well as ramifications, adaptation options and frameworks for decision-making within a number of areas discussed in chapter 30. Symbols are as follows: T = sea temperature; UW = upwelling; OA = ocean acidification; NU = nutrient concentration; IC = ice cover; SS = storm strength, SLR = sea level rise (□ = Increased; □ = decreased; italics = uncertain). Acronyms are: CBD (Convention on Biological Diversity), CTI (Coral Triangle Initiative), GEF (Global Environment Facility), IHO (International Hydrographic Organization), ILO (International Labour Organisation), IOM (International Organisation of Migration), ISPS (International Ship and Port Facility Security), LOSC (1982 Law of the Sea Convention), MARPOL (International Convention for the Prevention of Pollution From Ships), PACC (Pacific Adaptation to Climate Change Project), PEMSEA (Partnerships in Environmental Management for the Seas of East Asia), RFMO (Regional Fisheries Management Organisations), SPREP (Secretariat of the Pacific Regional Environment Programme), UNCLOS (United Nations Convention on the Law of the Sea), UNHCR (United Nations High Commissioner for Refugees), and WHO (World Health Organisation).

Primary driver(s)	**Biophysical change projected**	**Key risks and vulnerabilities**	**Ramifications**	**Adaptation options**	**Policy frameworks and initiatives (examples)**	**Key References**
↑T, ↑UW, *↑OA*	Changing primary productivity	Reduced fisheries production reduces important sources of income to some countries while others may see increase (e.g. as tuna stocks migrate eastwards in the Pacific with warming).	Reduced national income, increased unemployment, plus increase in poverty. Potential increase in disputes over national ownership of key fishery resources	Increased international cooperation over key fisheries. Improved understanding of linkages between ocean productivity, recruitment and fisheries stock levels. Implementation of the regional 'vessel day scheme', support industry as costs rise, stock characteristics change.	LOSC, PEMSEA, CTI, RFMO agreements	Tsamenyi and Hanich (2012); Bell et al. 2012, 2013; Section 30.6.1.1
↑T, *↑OA*	Ecosystem regime shifts (e.g. coral to algal reefs; structural shifts in phytoplankton community)	Reduced fisheries production as coastal habitats and ecosystems such as coral reefs and other coastal ecosystems degrade.	Decreased food and employment security and human migration away from coastal zone	Strengthen coastal zone management to reduce contributing stressors (e.g. coastal pollution, over-harvesting and physical damage to coastal resources). Promote blue carbon initiatives - restoration of coastal habitats such as mangroves, salt marshes and seagrass beds.	PEMSEA, CTI, PACC, MARPOL, UNHCR, CBD, IOM, GEF, ILO	Bell et al. 2012, 2013; Section 30.6.1.1
		Tourist appeal of coastal assets decreases as ecosystems change to less 'desirable' state reducing income to some countries.	Increased levels of coastal poverty in some countries as tourist income decreases.	As above, strengthen coastal zone management and reduce additional stressors on tourist sites; implement education programs and awareness among visitors. Diversify tourist activities to accommodate change in condition of local ecosystems.	CBD, PEMSEA, CTI, PACC, UNHCR, MARPOL	Kenchington and Warner (2012)
		Increased risk of some diseases (e.g. ciguatera may increase as temperatures increase shift and ecosystems shift away from coral dominance)	Increased disease and mortality; decreases in coastal food resources and fisheries income.	Increased monitoring and education surrounding key risks (e.g. ciguatera); develop alternate fisheries and income for periods when disease incidence increases.	National policy strategies as well as and regional cooperation needed	

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key References
		Increased poverty and dislocation of coastal people (particularly in the tropics) as coastal resources such as fisheries degrade.	Increased population pressure on migration destinations (e.g. large regional cities), and reduced freedom to navigate in some areas (as criminal activity increases).	Develop alternative industries and income for affected coastal people. Strengthen coastal security both nationally and across regions. Increase cooperation over criminal activities.	LOSC, PEMSEA, CTI, ISPS, IMO, Bali Process on Transnational Crime ASEAN Mutual legal Assistance treaty and bilateral extradition and MLA agreements	Rahman (2012), Kaye (2012),
↑T	Migration of organisms and ecosystems to higher latitudes.	Sudden reorganization of commercial fisheries due arrival of novel organisms and ecological regime shifts.	Social and economic disruption over short periods of time.	Increased international cooperation and improve understanding of regime changes; provide increased monitoring of physical and biological variables; include related uncertainties into fisheries management; support industry as costs rise, stock characteristics change. change.	LOSC, CBD, RFMO agreements	
		Increased risks from pests and fouling as new species arrive at higher latitudes.	Increased damage to coastal ecosystems, aquaculture and fisheries. Income loss and increased costs associated with responding.	Increase monitoring of changes to community and ecosystem structure; provide assistance to industry impacted by pest and fouling organisms; control contributing factors such as the transport of invading organisms on ships hulls and in ballast water.	IMO, BWM, Anti Fouling Convention	
		Threats to human health increase due to the arrival of new pathogens at higher latitudes.	Increased disease and mortality in some coastal communities.	Reduce exposure through increased monitoring and education	UNICEF, WHO, IHOs, and national governments.	Myers and Patz (2009)
↑T, ↑NU, ↑*OA*	Increased incidence of harmful algal blooms (HABs).	Increased threats to ecosystems, fisheries and human health.	Reduced food and greater incidence of disease among some coastal communities.	Reduce nutrient run-off and other contributing issues; improve understanding of how related variables facilitate increased incidence of HABs.	CTI, PEMSEA, MARPOL	
↑T	Increased precipation as a result of intensified hydrological cycle in some coastal areas	Increased freshwater, sediment and nutrients flow into coastal areas.	Increasing damage to coastal reef systems with ecological regime shifts in many cases.	Improve management of catchment and coastal processes; expand riparian vegetation along creeks and rivers; improve agricultural retention of soils and nutrients.	CTI, PEMSEA, SPREP	

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key References
↑T	Changing weather patterns (local climates, storm intensity)	Increased risk of damage to infrastructure such as that involved in shipping, and oil and gas exploration and extraction.	Increased damage and associated costs	Adjust infrastructure specifications for new conditions and developed more advanced monitoring and warning systems.	IMO	
↑SLR, ↑*SS*	Increased wave exposure of coastal areas	Exposure of coastal infrastructure and communities to damage and inundation	Increased costs to human towns and settlements, numbers of displaced people and human migration.	Develop integrated coastal plans that consider SLR in planning and decision making; increase understanding of the issues through education.	UNICEF, IHOs, and national governments.	Warner (2010)
		Inundation of coastal aquifers reduces water supplies and decreased coastal agricultural productivity.	Reduced food and water security leads to increased coastal poverty, reduced food security, and migration.	Assist communities to find alternatives for food and water, or assist in relocation from vulnerable areas.	UNICEF, IHOs, and national governments.	Warner (2010) CHAPTER 5 linkages
↑SLR	High tide mark moves inland, especially in low-lying countries.	UNCLOS defined limits of maritime jurisdiction will contract as national baselines shift inland. Potential uncertainty increases in some areas with respect to the international boundaries to maritime jurisdiction.	Lack of clarity increases as do disputes over maritime limits and maritime jurisdiction. Some nations at risk of major losses to their territorial waters.	Seek resolution of 'shifting national baselines' issue (retreat and redefinition, stabilization, or fixation of EEZ and other currently defined maritime jurisdiction limits.	LOSC, UNCLOS	Schofield and Arsana (2012); Warner and Schofield (2012)
↑T, ↓IC	Loss of summer sea ice	Access to northern coasts of Canada, USA and Russia increases security concerns.	Potential for increased tension on different interpretations.	Seek early resolution of areas in dispute currently and in the future.	LOSC, UNCLOS	WGII Chapter 28
		New resources become available as ice retreats, increasing vulnerability of international borders in some cases.	Tensions over maritime claims and ownership of resources.	International agreements need to be sort.	LOSC, UNCLOS	

A



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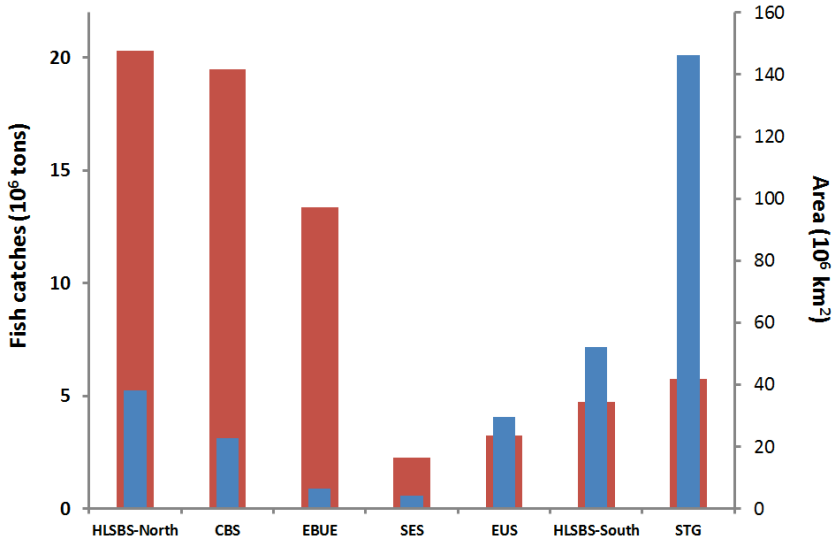


Figure 30-1: A. The world's non-polar oceans have been separated into seven major sub-regions, with polar oceans being excluded due to treatment elsewhere (Ch28). The chlorophyll concentration averaged over the period from Sep 1997 – 30 Nov 2010 (NASA) is also shown. Together with key oceanographic features, primary production was the basis for separating the ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). Numbers refer to: 1 = High Latitude Spring Bloom Systems (HLSBS), 2 = Equatorial Upwelling (EUS), 3 = Semi-enclosed seas (SES), 4 = Coastal Boundary Systems (CBS), 5 = Eastern Boundary Upwelling Ecosystems (EBUE), 6 = Subtropical gyres (STG), and 7 = Deep sea (>1000 m). B. relationship between fish catch and areas for Ocean sub-regions shown in A. Red columns: average fish catch (millions tons yr^{-1}) for the period 1970-2006. Blue columns: area (millions km^2).

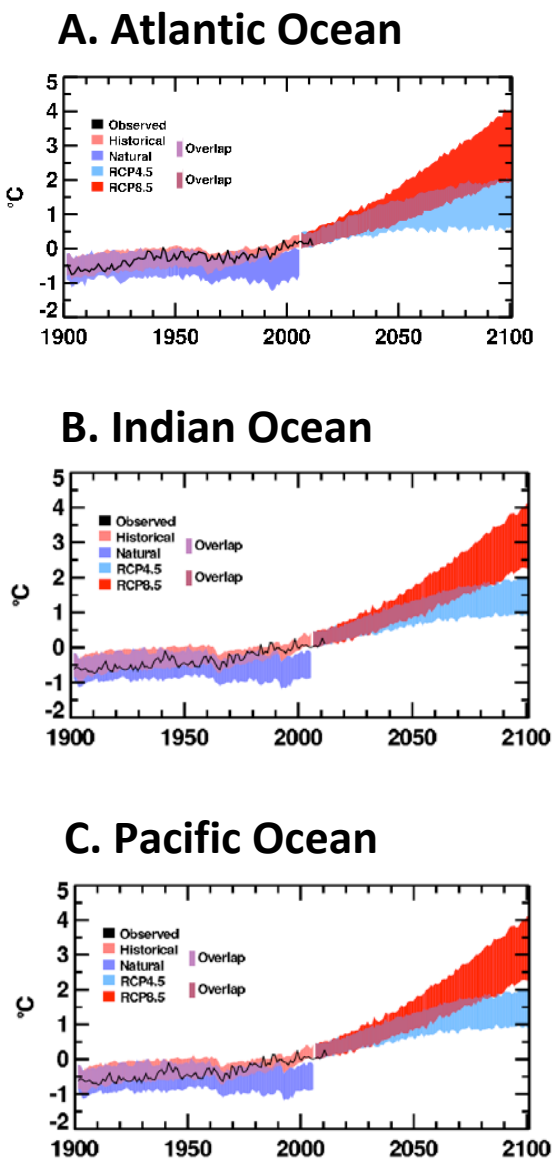


Figure 30-2: Observed and simulated variations in past and projected future annual average sea surface temperature over various oceanic regions. The black line shows estimates from HadISST1 observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), the "RCP4.5" emissions scenario (62), and the "RCP8.5" (62). Data are anomalies from the 1986-2006 average of the HadISST1 data (for the HadISST1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.

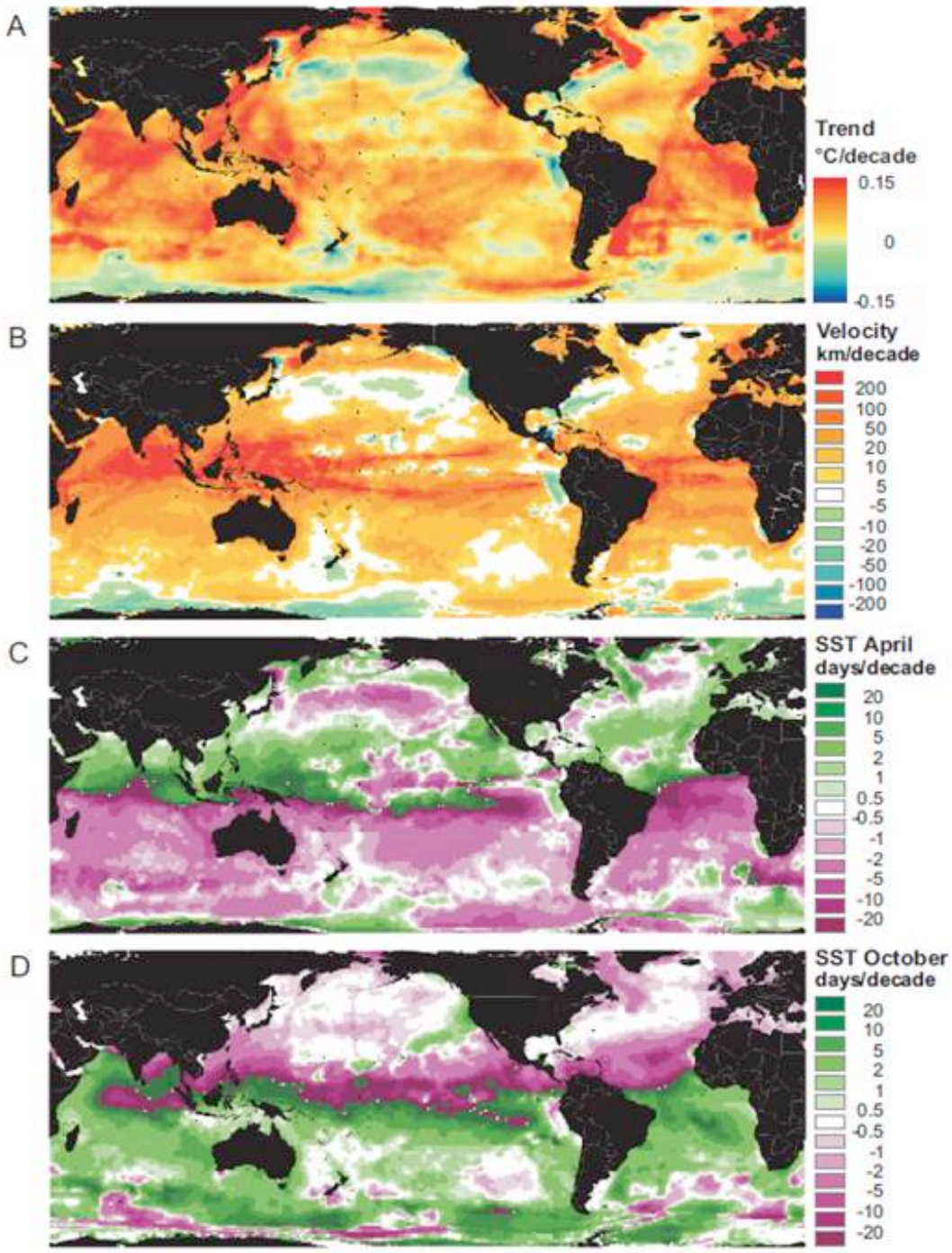


Figure 30-3: Analysis of data from Hadley Centre (HadISST 1.1, [*Rayner et al.*, 2003]) for different ocean sub-regions. A. Rate of change in sea surface temperature over the past 30 years (°C. decade^{-1}). B. Velocity at which isotherms are moving (km.decade^{-1}) from 1960-2009. C. Shift in seasonal changes that drive natural history events (days.decade^{-1}) for April and D. for October. E.

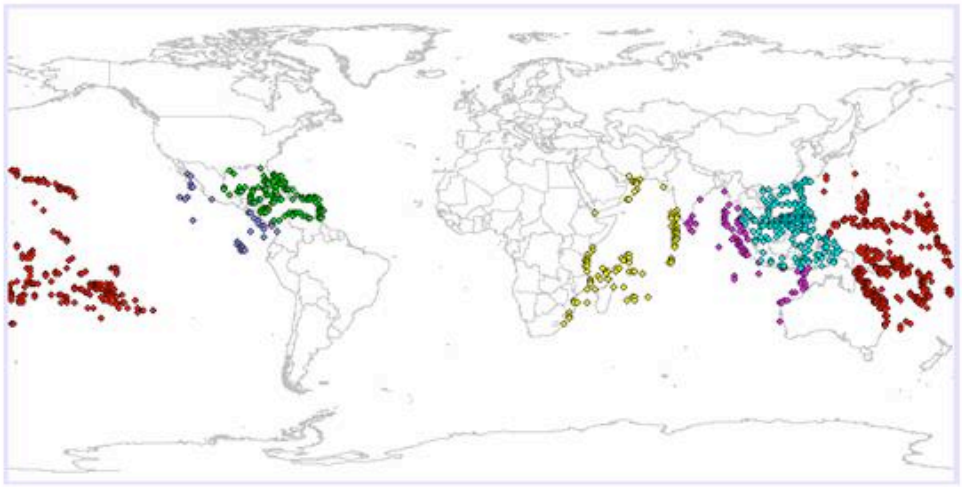


Figure 30-4: Location of coral reef grid cells used in Tables 30.2 and 30.4 as well as in Figure 30.11. Each dot is centred over a 1x1 degree grid cell within which lies at least one coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk (http://www.wri.org). The six regions are as follows: Red – Western Pacific; Blue – Eastern Pacific Ocean; Green – Caribbean & Gulf of Mexico; Yellow – Western Indian Ocean; Magenta – Eastern Indian Ocean; and Cyan – Coral Triangle & SE Asia.

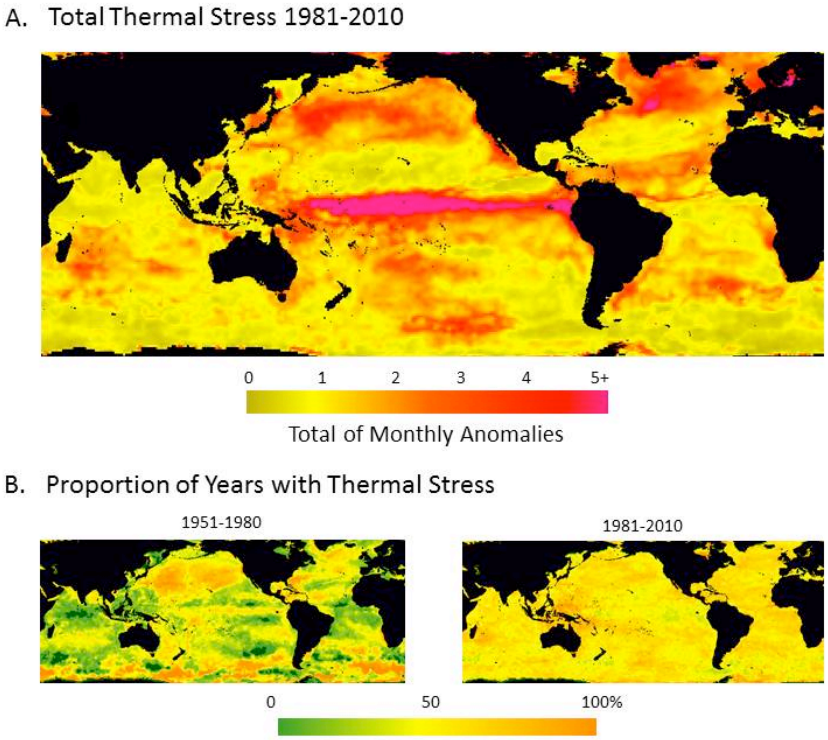


Figure 30-5: Recent changes in thermal stress calculating using HadISST 1.1 data. A monthly climatology was created by averaging the HadISST monthly SST values over the period 1985-2000 to create twelve averages, one for each month of the year. The Maximum Monthly Mean (MMM) climatology was then created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each SST value, but only allowing values to be recorded if they were greater than zero (Donner et al., 2007). Three measures of thermal stress change were then created: (A) Total thermal stress for the period 1981-2010, calculated by summing all monthly thermal anomalies for each grid cell. (B) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951-1980 and (C) 1981-2010.

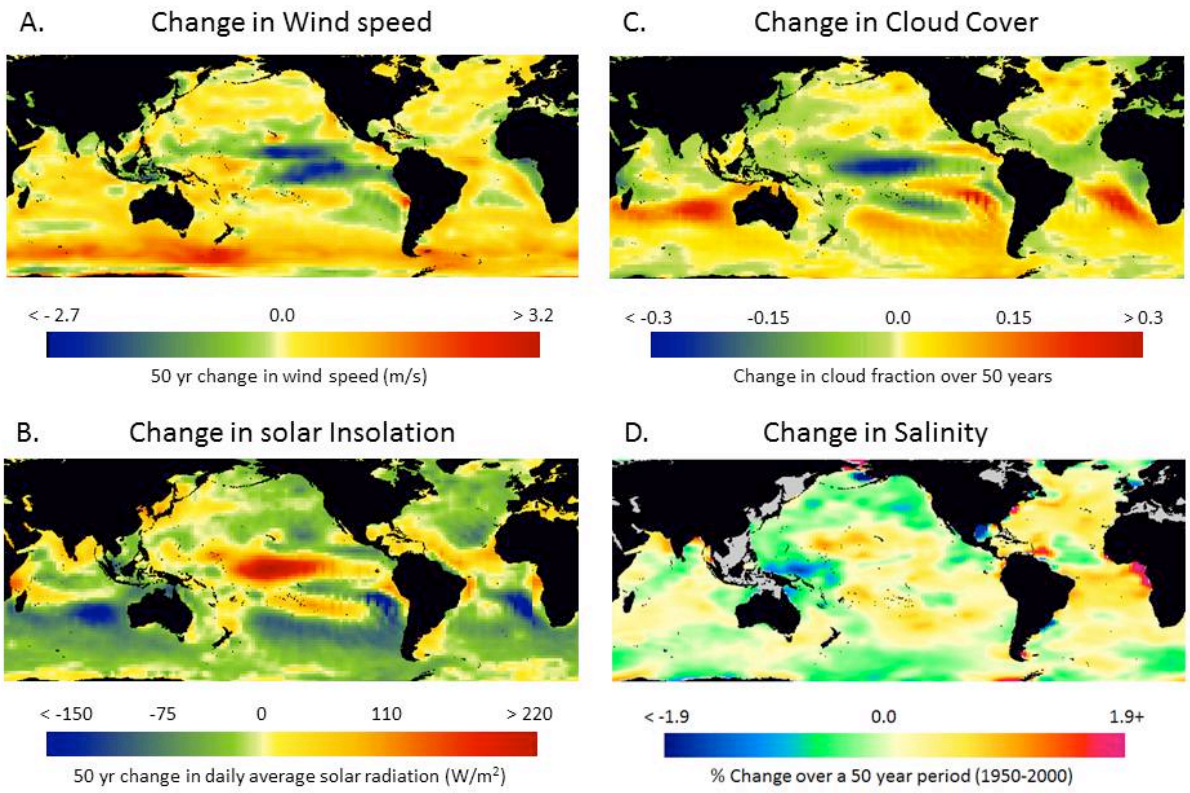


Figure 30-6: Absolute change over 50 years calculated using regression analysis of data from 1951-2010 (A) Wind Speed as the absolute change in $m.s^{-1}$; (B) Solar radiation as change at the surface of incoming solar insolation in Wm^{-2}; (C) Cloud Cover as the absolute change in total cloud fraction (i.e. If at the beginning of the period the cloud fraction was 0.6 and 0.5 at the end of the period, the change would be -0.1) using NCEP re-analyzed data (www.esrl.noaa.gov); and (D) Salinity as the percentage change from 1960-2010 [reproduced using the data of Durack and Wijffels, 2010]. Data for (A), (B) and (C) were derived from the NCEP/NCAR Reanalysis [*Kanamitsu et al*., 2002]. Monthly mean values for wind speed, total cloud cover and downward solar radiation flux (solar insolation) were obtained from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html. At each 1x1 degree grid cell, a linear regression was calculated for each of wind, cloud and solar insolation. The slopes were then multiplied by 600 (months) to calculate the average change over a 50 year period.

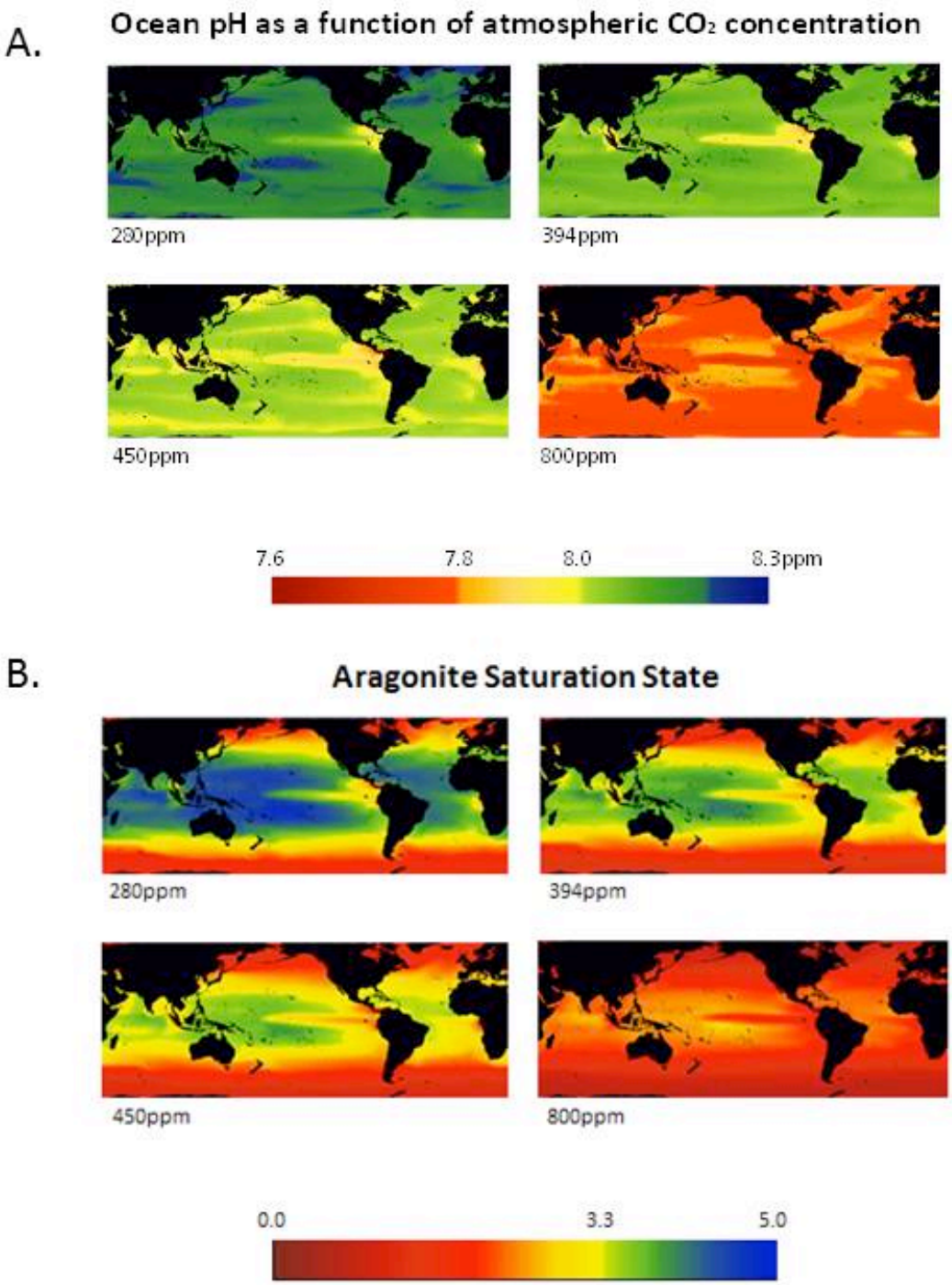


Figure 30-7: A. Surface pH and B. aragonite saturation state of the Ocean at different atmospheric CO_2 levels simulated by the University of Victoria Earth System Model. The fields of pH and aragonite saturation state are calculated from the model output of dissolved inorganic carbon concentration, alkalinity concentration, temperature, and salinity, together with the chemistry routine from the OCMIP-3 project (http://www.ipsl.jussieu.fr/OCMIP/phase3).

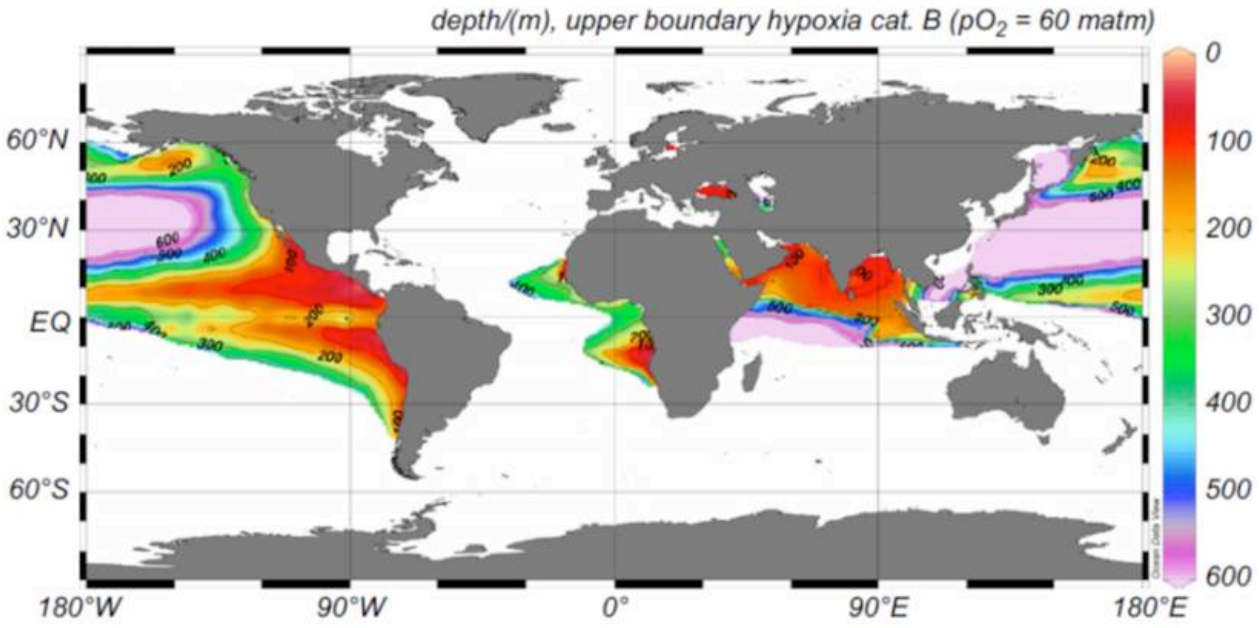


Figure 30-8: Map of the depth [*Hofmann et al.*, 2011] at which a critical value of partial pressure of O_2 of 60 matm occurs which is widely accepted as threatening to marine life on continental shelves (200m depth). Conventional maps of oceanic oxygen values report simple mass properties with no temperature or depth dependence; a better rendition of the availability of O_2 to marine life is provided by the partial pressure, which includes the temperature terms. Critical sub-regions in the eastern and northern Pacific and in the northern Indian ocean stand out. In these areas quite modest upward expansion of the depth at which the critical pO_2 level occurs can have negative effects on major fish populations. Note: not all areas have been included – for example, significant hypoxia in the Gulf of Mexico is not been shown.

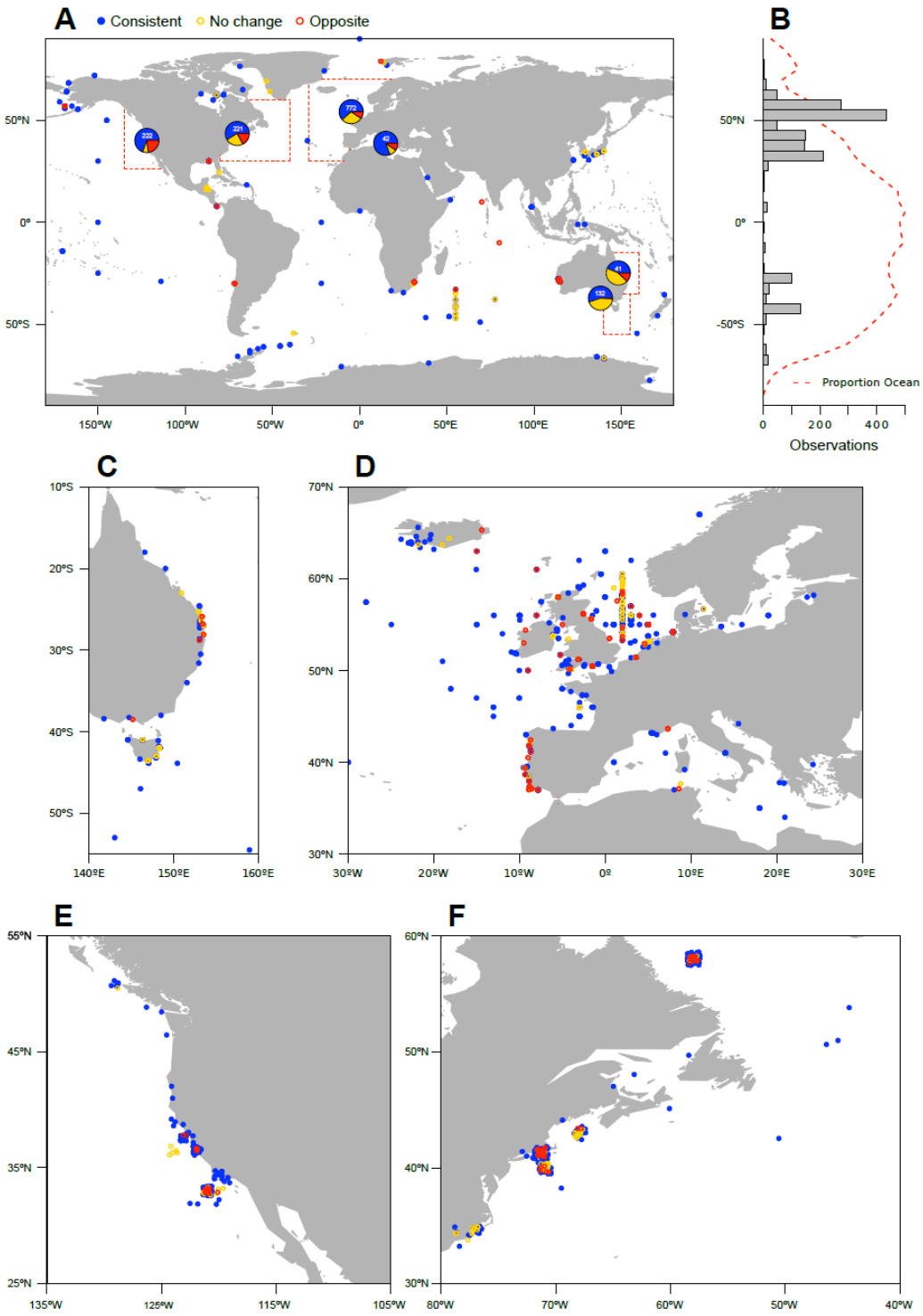


Figure 30-9: (A) 1735 observed responses to climate change from 208 single- and multi-species studies showing responses that are consistent with climate change (blue), opposite to expected (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite plus equivocal) observations within each region. (B) Frequency of observations by latitude. (C) South-west Pacific. (D) North-east Atlantic. (E) California Current. (F) North-west Pacific (Poloczanska et al 2013).

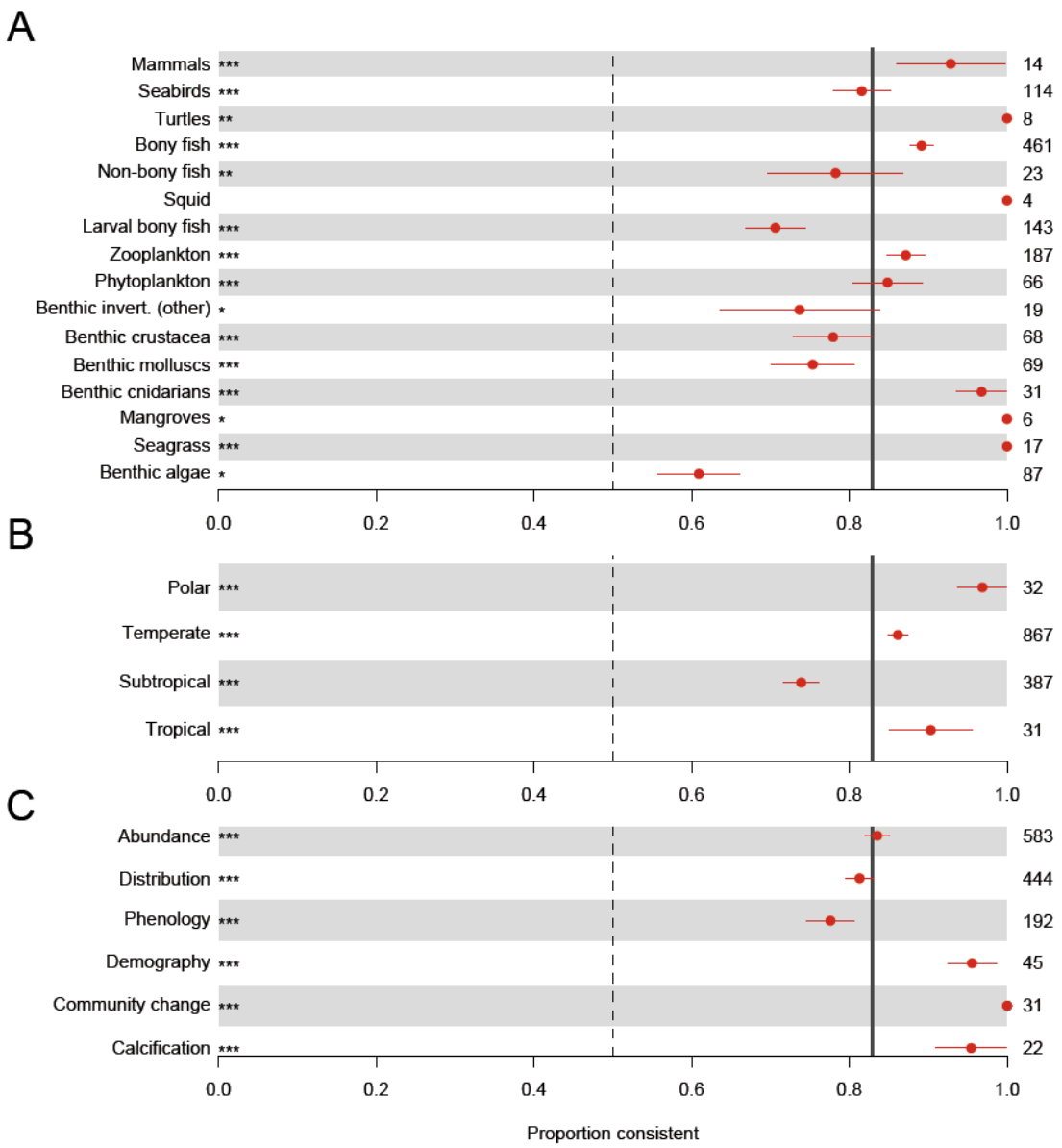


Figure 30-10: Percent of responses consistent with climate change predictions. Mean and standard error of responses by (A) taxa, (B) latitudinal region and (C) response measure show significantly higher consistency than expected from random (dashed line at 50% consistency). Solid line is the mean across all observations. Significance of results is listed next to labels (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Sample sizes are listed to the right of each row.

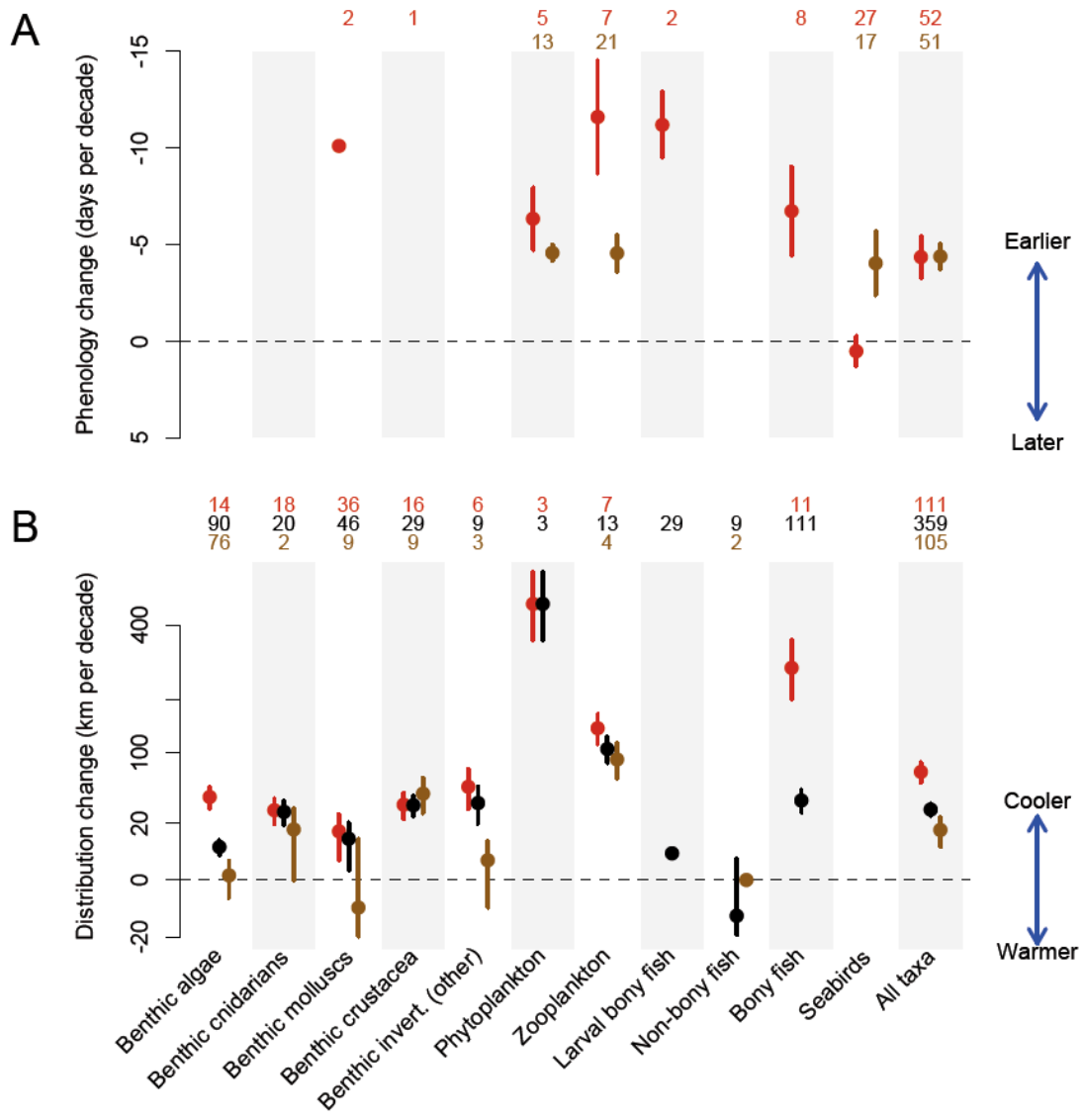


Figure 30-11: Rates of change in (A) phenology (days.decade^{-1}) measured during spring (red) and summer (brown); and (B) distribution (km.decade^{-1}) for marine taxonomic groups, measured at the leading edges (red), and trailing edges (brown). O (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward) and negative phenological changes are consistent with warming (generally earlier). Means ± standard error are shown, with number of observations and significance (*p<0.1, **p<0.05, ***p<0.01); Poloczanska et al, 2013).

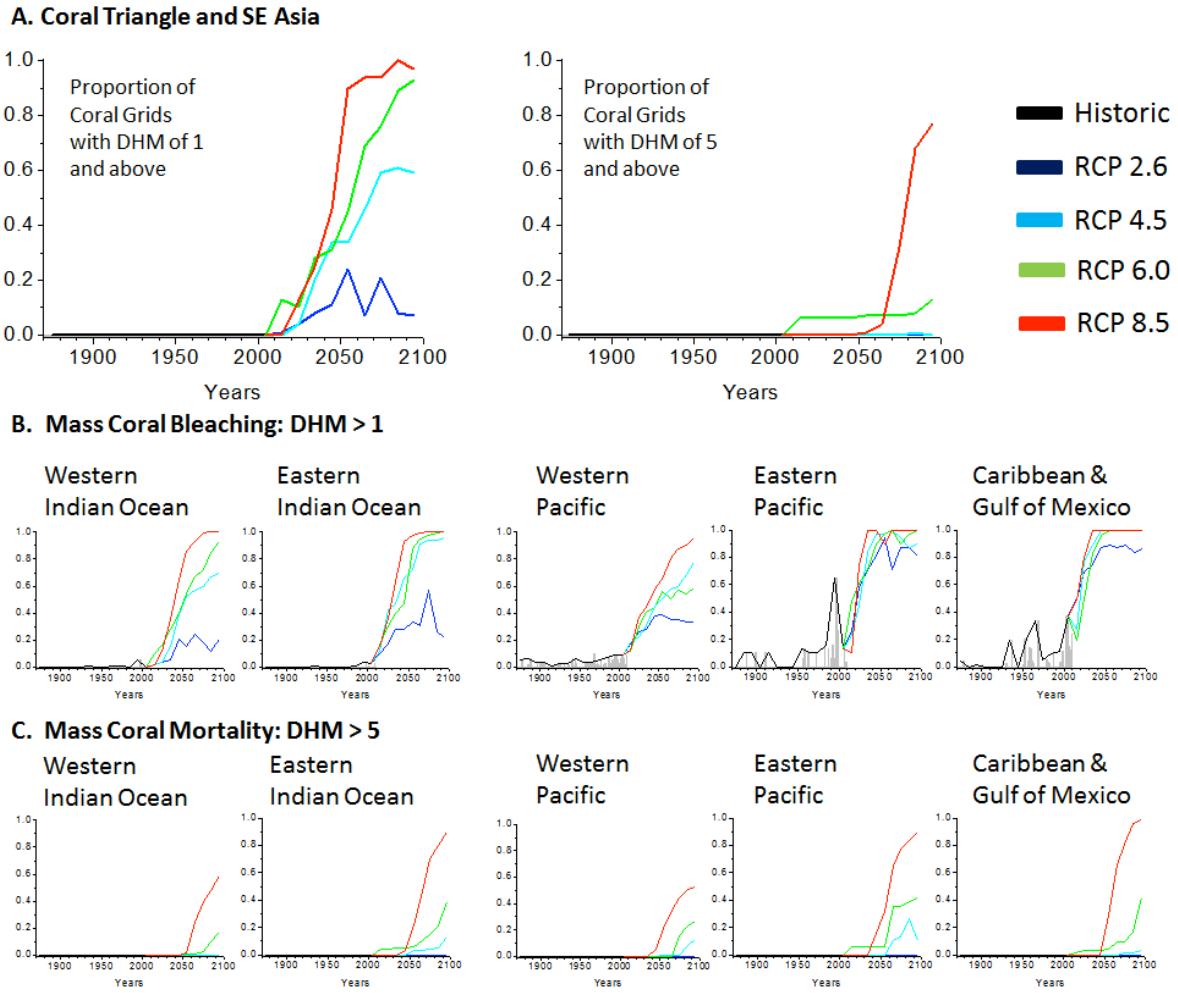


Figure 30-12: Annual maximum proportions of reef pixels with Degree Heating Months (Donner et al. 2007; DHM) ≥ 1 (coral bleaching) and DHM ≥ 5 (bleaching across 100% of affected areas with significant mortality, Eakin et al. 2010) for each of the six coral regions (Figure 30.3) have been depicted as bar graphs for the period 1870-2009. This part of the graph is derived from the HadISST 1.1 data set. The black line plotted on top of the bar graphs is the maximum annual area value for each decade over the period 1870-2009. This value is continued through 2010-2099 using CMIP-5 data and splits into the four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0 and 8.5). DHMs were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHMs the annual percentage of grid cells with DHM ≥ 1 and DHM ≥ 5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010-2099 are the average of these maximum proportion values for each RCP. Monthly SST anomalies are derived using a 1985-2000 maximum monthly mean (MMM) climatology derived in the calculations for Figure 30.4. This was done separately for HadISST 1.1 and each of the CMIP-5 models and each of the four RCPs, at each grid cell for each region. DHMs are then derived by adding up the monthly anomalies using a 4 month rolling sum.

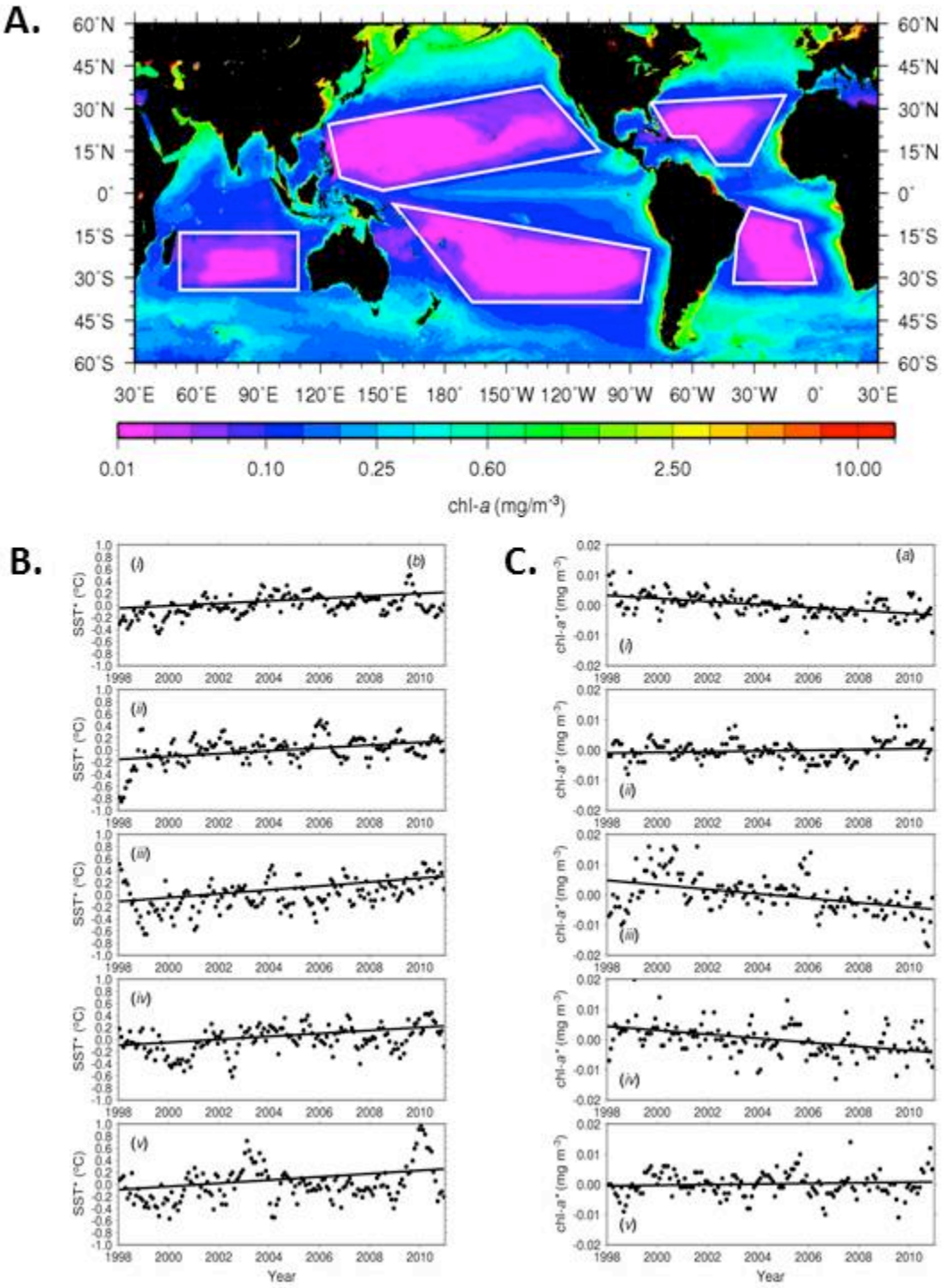


Figure 30-13: A. Map of SeaWiFS chl-a climatology. The white polygons define the sub-regions that were analyzed and represent the major sub-regions considered as sub-tropical gyres by Signorini and McClain (2012). B. Time series of anomalies in chl-a and B. Sea Surface Temperature SST for STGs in North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE) North Atlantic (NATL) and South Atlantic (SATL) Oceans.

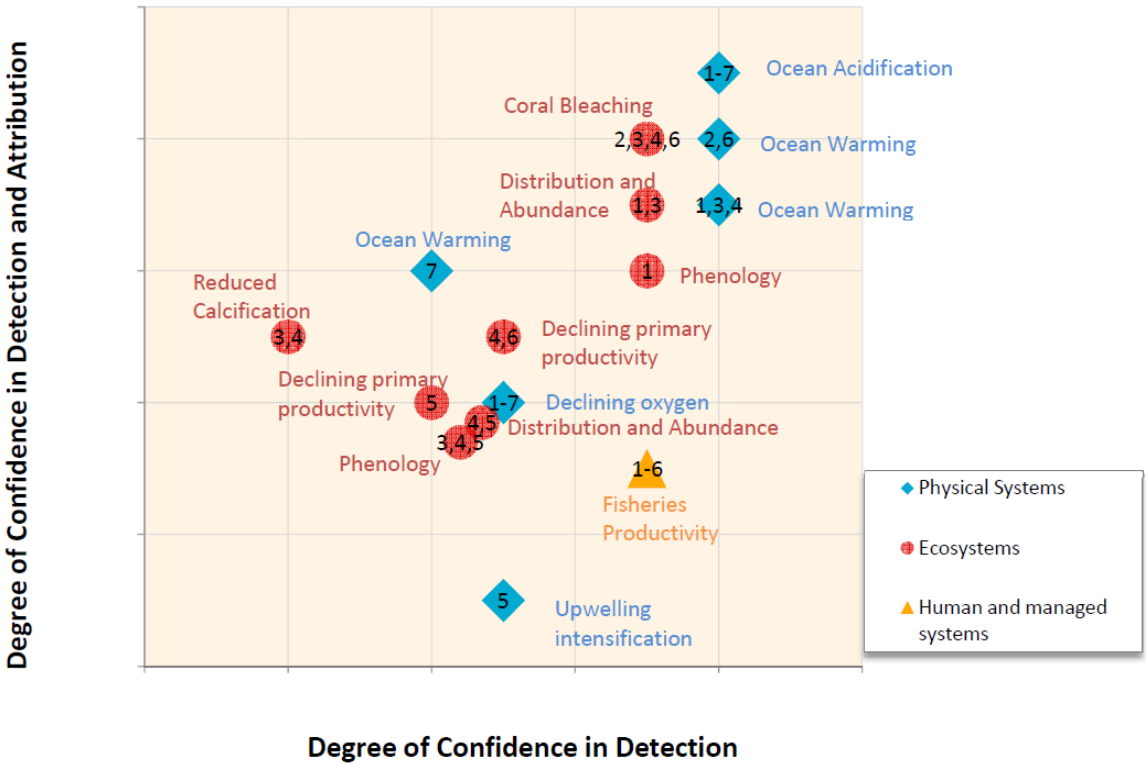


Figure 30-14: Expert assessment of degree of confidence in detection and attribution across sub-regions and processes (based on evidence explored throughout Chapter 30).

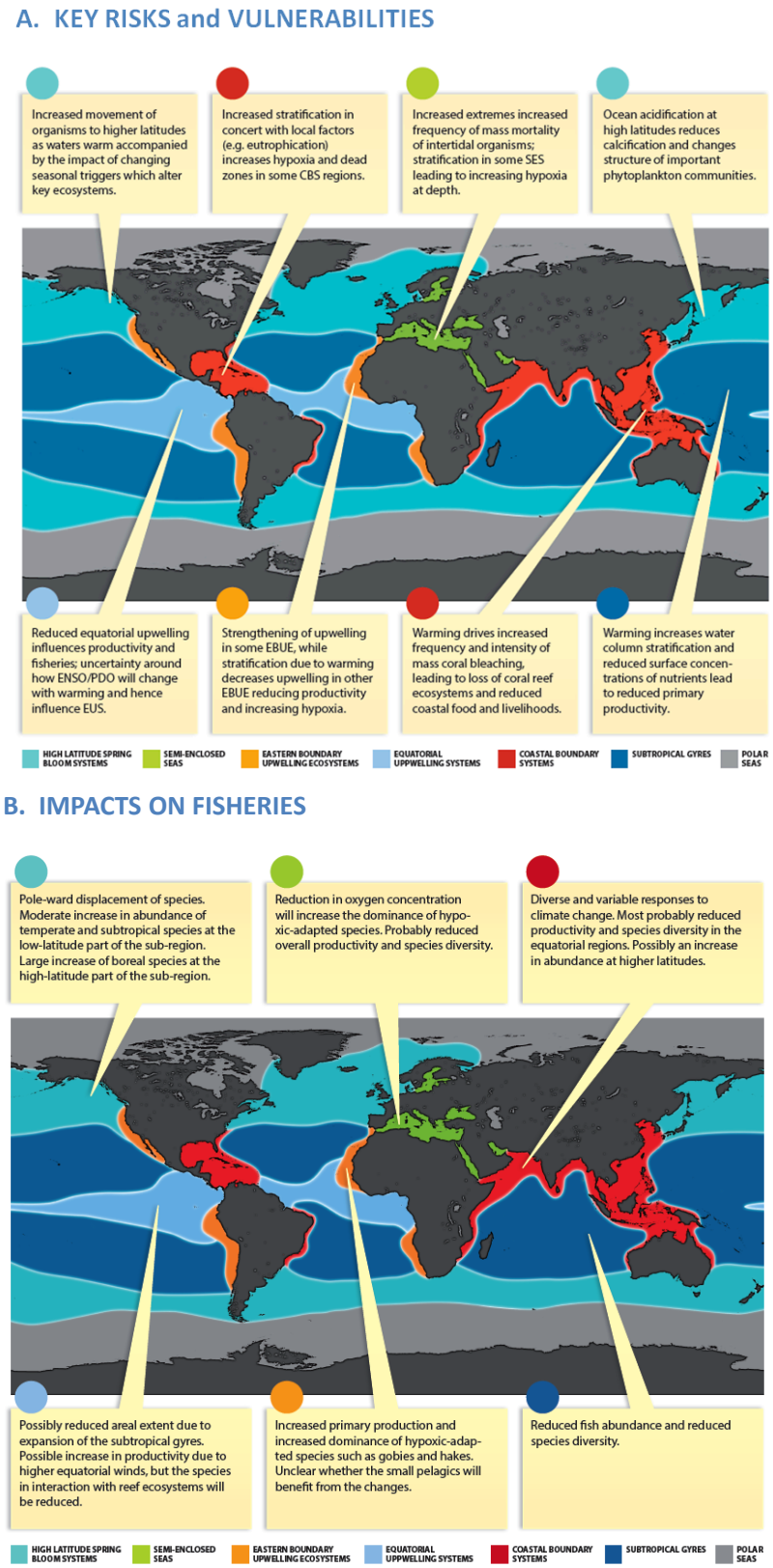
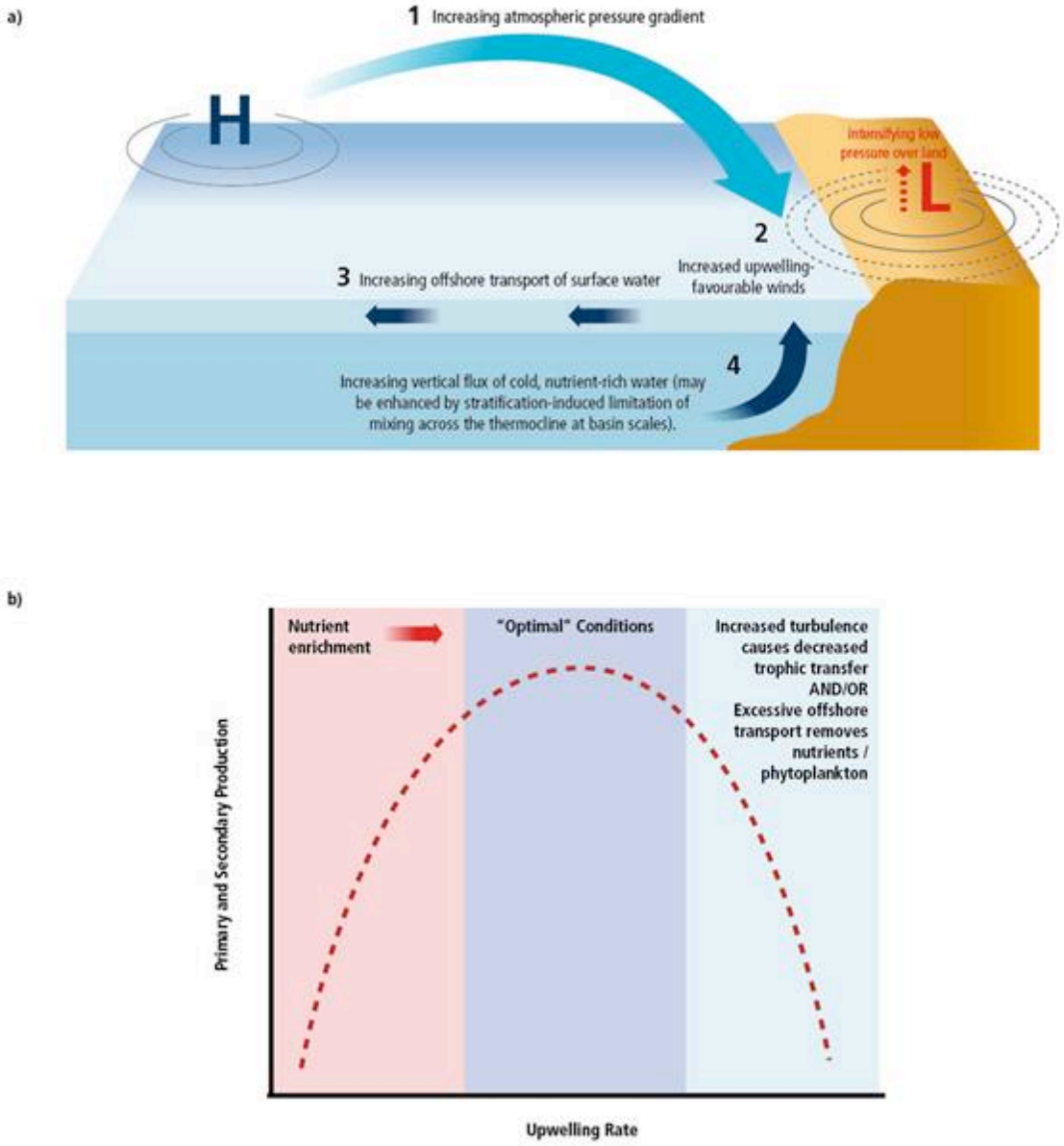


Figure 30-15: A. Summary of regional impacts and opportunities associated with climate change on the world's ocean region. B. Example of changes occurring within fisheries across the Ocean.



Box 30-1 Figure Caption: Diagram illustrating the interaction between land and coastal sea temperature, wind direction and strength, and coastal upwelling.

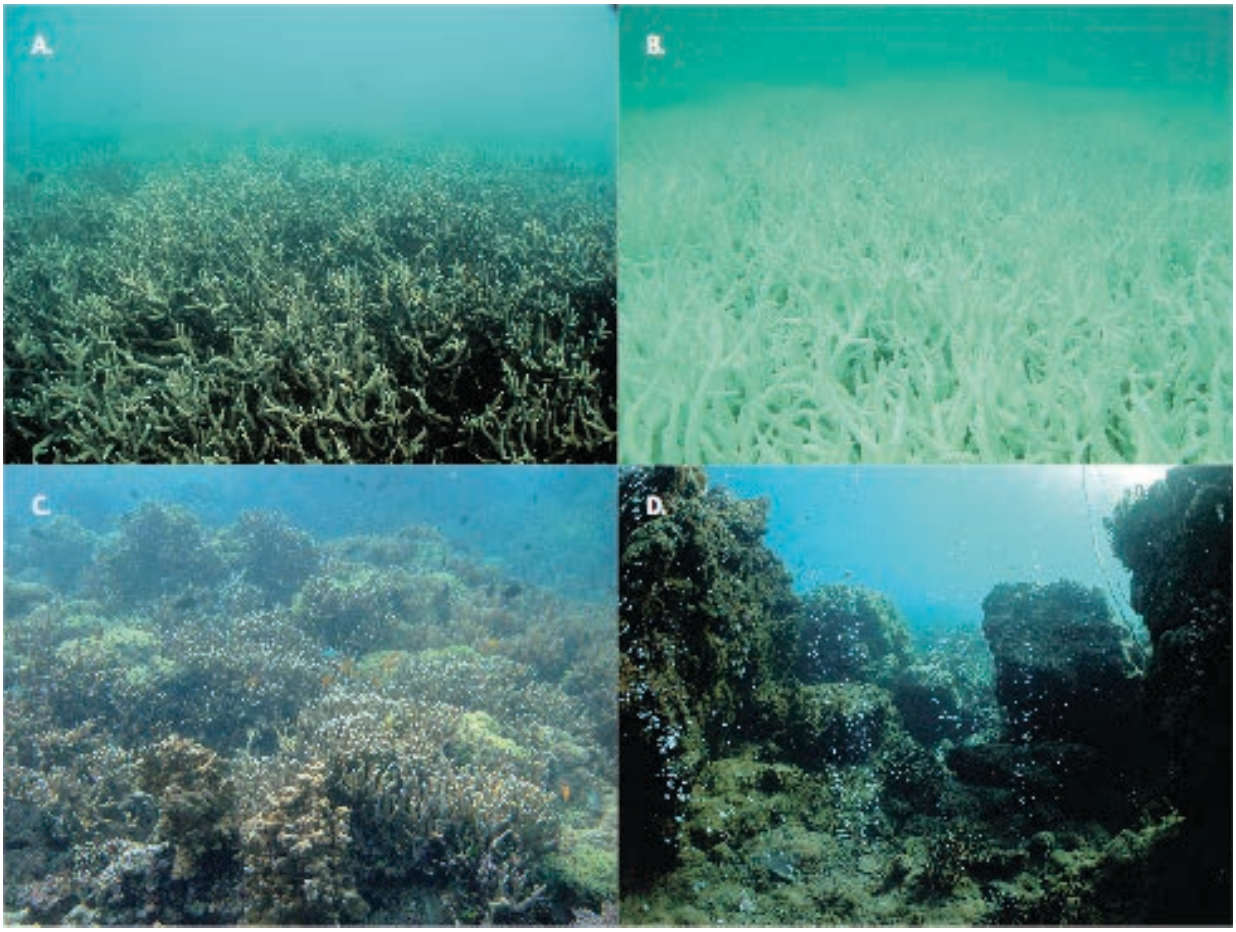


Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge et al., 2004). Mortality was comparatively low due in part because these communities were able shuffle symbiont types to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones et al., 2008). C and D: three CO2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO2 is related to fundamental changes in coral reef structures (Fabricius et al., 2011). Coral communities at three high CO2 (Fig. XB; median pHT 7.7, 7.7 and 8.0), compared with three control sites (Fig. XA; median pHT 8.02), are characterized by significantly reduced coral diversity (-39%), severely reduced structural complexity (-67%), low densities of young corals (-66%) and few crustose coralline algae (-85%). Reef development ceases at pHT values below 7.7. Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

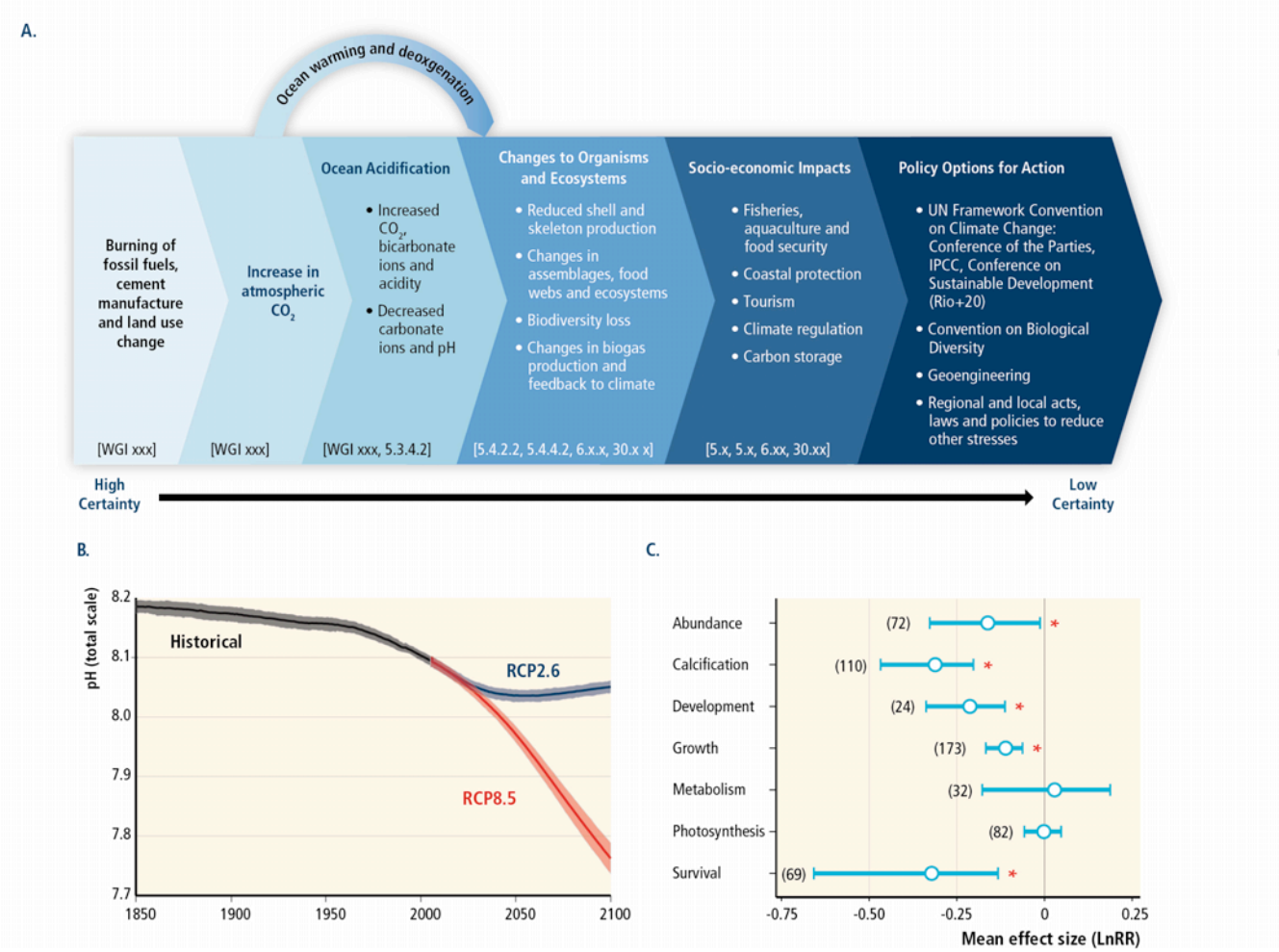


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.